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BASE CATION DEPOSITION IN WESTERN CANADA (1982–1998)

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BASE CATION DEPOSITION IN WESTERN CANADA (1982–1998)

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February 2001

Pub. No: T/605
ISBN: 0-7785-1715-2 (Printed Edition)
ISBN: 0-7785-1716-0 (On-Line Edition)
Web Site: http://www.gov.ab.ca/env/

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SUMMARY

Base cation deposition was investigated for 31 precipitation monitoring stations in western Canada. Using precipitation chemistry data from each station, wet, dry, and total deposition of the base cations Na^+, Ca^{2+}, Mg^{2+}, and K^+ were analyzed over the general time period of 1982–1998. A spatial analysis was performed using shaded contour plots of the deposition data to contrast the magnitude of deposition between stations in the study area.

Air concentrations of the base cations were estimated using precipitation concentrations from each station and the scavenging ratio. A linear regression derived by Eder and Dennis (1990) from Ontario base cation data was applied to the stations in western Canada. The results of this 'Ontario regression', as it is referred to in this report, were then compared to directly measured air concentrations at Beaverlodge and Esther. The Beaverlodge and Esther data were also used to derive a new set of regression equations, referred to as the 'Alberta regression' in this report, for application to western Canada.

The greatest magnitude of base cation deposition was found at Port Hardy in western British Columbia. Most of the deposition in western Canada was Na^+ deposition; however, Ca^{2+} deposition was also relatively great, especially in central Alberta. Mean annual wet deposition ranged from 0.030 to 1.009 keq/ha. Mean annual dry deposition estimates ranged from 0.058 to 0.682 keq/ha, based on the Ontario regression, and 0.042 to 0.140 keq/ha based on the Alberta regression. The Alberta regression gave dry deposition values that were lower than wet deposition values; however, the Ontario regression gave dry deposition values that were higher than wet deposition values in western Canada.

The Alberta regression resulted in lower deposition values than did the Ontario regression. Although the two sets of regression equations gave different magnitudes of base cation deposition, they gave the same spatial variation in base cation deposition. The greatest deposition was estimated for western British Columbia, mainly as a result of Na^+. Both regressions also found that base cation deposition has generally decreased in western Canada since the 1980s; however, the Alberta regression gave less of a decrease than did the Ontario regression.

The Ontario regression did not work for estimating air concentrations of base cations in western Canada. The air concentrations estimated by the Ontario regression did not agree with the concentrations directly measured at Beaverlodge and Esther. While the Alberta regression provides an alternative method for analyzing base cations in western Canada, it cannot be tested due to the lack of measured air concentration data in western Canada. Additional base cation data are needed from this region in order to clarify the relationship between air concentrations and precipitation concentrations of base cations in western Canada.

TABLE OF CONTENTS

1.0 INTRODUCTION **1**

2.0 DATA AND ANALYSIS METHODS **3**

2.1 Data Source *3*

2.2 Wet Deposition *3*

2.3 Dry Deposition *6*

2.4 Total Deposition *7*

3.0 WET DEPOSITION **9**

3.1 Precipitation Concentrations *9*

3.2 Mean Annual Wet Deposition *9*

3.3 Wet Deposition Trends *12*

3.4 Wet Deposition Variability *12*

4.0 DRY DEPOSITION **19**

4.1 Air Concentrations *19*

4.1.1 Estimates Using Eder-Dennis Equations 19

4.1.2 Estimates Using Relationships from Beaverlodge and Esther Data 23

4.2 Mean Annual Dry Deposition *24*

4.2.1 Estimates Using Eder-Dennis Equations 24

4.2.2 Estimates Using Relationships from Beaverlodge and Esther Data 24

5.0 TOTAL DEPOSITION **31**

5.1 Estimates Using Eder-Dennis Equations *31*

5.2 Estimates Using Relationships from Beaverlodge and Esther Data *31*

6.0 CONCLUSIONS **37**

7.0 REFERENCES **39**

8.0 APPENDIX **A1**

LIST OF FIGURES

Figure 2.1 Study area. 4

Figure 3.1 Distribution of variation coefficients for average precipitation concentrations.... 10

Figure 3.2 Mean annual wet deposition (keq/ha) of Na^+, Ca^{2+}, Mg^{2+}, and K^+ 13

Figure 3.3 Mean annual wet deposition of all base cations (keq/ha) 14

Figure 3.4 Trends in mean annual wet deposition of base cations (keq/ha/y) 16

Figure 3.5 Distribution of variation coefficients for annual wet deposition 18

Figure 4.1 Comparison of air concentrations measured at Beaverlodge to those calculated using the Ontario (Eder-Dennis) regression 21

Figure 4.2 Comparison of air concentrations measured at Esther to those calculated using the Ontario (Eder-Dennis) regression 22

Figure 4.3 Scatter plots of base cation precipitation and surface-level air concentrations in Alberta 23

Figure 4.4 Mean annual dry deposition of base cations (keq/ha), based on Ontario regression 26

Figure 4.5 Mean annual dry deposition of base cations (keq/ha), based on Alberta regression 29

Figure 5.1 Mean annual total base cation deposition (keq/ha), based on Ontario regression 33

Figure 5.2 Mean annual total base cation deposition (keq/ha), based on Alberta regression. 34

Figure AI.1 Mean annual precipitation (mm) A4

Figure AI.2 Ratio of mean annual dry deposition to mean annual wet deposition for all cations, based on Ontario regression A9

Figure AI.3 Ratio of mean annual dry deposition to mean annual wet deposition for all cations, based on Alberta regression A10

LIST OF TABLES

Table 2.1 Precipitation monitoring stations: abbreviations, locations, and record lengths 5

Table 2.2 Eder-Dennis (Ontario) linear regression equations 6

Table 3.1 Average annual wet deposition (keq/ha) 11

Table 3.2 Annual wet deposition trends (keq/ha/y) 15

Table 4.1 Stations where negative Ca^{2+} concentrations were calculated using the Eder-Dennis (Ontario) equations 20

Table 4.2 Alberta (Beaverlodge and Esther) linear regression equations 23

Table 4.3 Mean annual dry deposition and annual dry deposition trends, using Ontario regression 25

Table 4.4 Mean annual dry deposition and annual dry deposition trends, using Alberta regression 27

Table 5.1 Total deposition in western Canada, based on Ontario and Alberta regressions .. 32

Table AI.1 Coefficient of variation for average precipitation concentrations in a year (%) .. A3

Table AI.2 Average annual wet deposition (keq/ha) A5

Table AI.3 Annual wet deposition trends (keq/ha/y) A6

Table AI.4 Standard deviation of annual wet deposition (keq/ha) A7

Table AI.5 Coefficient of variation for annual wet deposition of base cations (%) A8

LIST OF EQUATIONS

(1) Wet deposition 3

(2) Dry deposition 7

(3) Total deposition 7

ACKNOWLEDGEMENTS

This project was facilitated by Lawrence Cheng of Alberta Environment. The precipitation monitoring data were supplied from the Canadian National Atmospheric Chemistry (NAtChem) Database of Environment Canada's Atmospheric Environment Service. Air quality data were acquired from the Enforcement and Monitoring Division of Alberta Environment, as well as from the Atmospheric and Hydrological Science Division of Environment Canada, Edmonton. Base maps of the provinces and territories in the study area were provided by Jamie Ayers of Alberta Environment.

Special thanks are due to Lawrence Cheng, Randy Angle, Ken Foster, and Lisa Holmes of Alberta Environment for reviewing this report.

1.0 INTRODUCTION

Base cations are positively charged particles that can be found in the atmosphere as a part of aerosols and particulate matter. The predominant base cations, sodium ions (Na^+), calcium ions (Ca^{2+}), magnesium ions (Mg^{2+}), and potassium ions (K^+) may occur in the atmosphere as a result of natural or anthropogenic processes (Gorham, 1994). Anthropogenic sources can include agricultural tillage, traffic on unpaved roads, and particulates from urban and industrial smokestacks (Gorham, 1994; Draaijers et al., 1995; Semb et al., 1995). Some natural sources of base cations are wind erosion of soils, forest fires, and pollen transport (Draaijers et al., 1995). Alkaline emissions from industry are relatively minor compared to open sources such as soils and unpaved roads (Gatz et al., 1986).

Base cations play two major ecological roles in the environment: (1) ion exchange in terrestrial soils ecosystems (Cheng et al., 1997), which includes acting as a nutrient source to vegetation, and (2) contribution to the chemical processes of acid deposition (Draaijers et al., 1995). With respect to the latter role, base cations neutralize acid input by raising the pH of rainfall, thereby reducing acid deposition damage (Gorham, 1994 and CASA, 1999). At the surface, greater concentrations of base cations in soil or water increase the buffering capacity, making the receptor less sensitive to chemical change due to acid deposition (Target Loading Subgroup, 1999).

The process of acid deposition involves acidic species, which are formed in the atmosphere, being deposited at the earth's surface by way of two transport mechanisms. The transport of dissolved species to the surface via precipitation is called *wet* deposition, while the transport of gaseous species or small particles without dissolution is called *dry* deposition (Finlayson-Pitts and Pitts, 2000). With dry deposition, the gases or small particles can directly interact with soil, vegetation, and water (CASA, 1999), for example, by being absorbed or adsorbed by surface materials.

Acid precipitation is formed in air containing oxides of sulphur (SO_x) and oxides of nitrogen (NO_x), which result from fuel combustion, electric power generation, and industrial and motor vehicle emissions (Moran and Morgan, 1997). Gaseous SO_x and NO_x react with moisture in the atmosphere to form sulphuric acid and nitric acid (respectively), which dissolve in precipitation and increase its acidity. This type of acid deposition is commonly referred to as "acid rain". Detrimental effects of acid rain can include degradation of aquatic and terrestrial ecosystems, leaching of beneficial cations from ecosystems (Gorham, 1976), or even corrosion of metals and erosion of stone and brick structures (CASA, 1999).

In the same manner as acid deposition, base cations are deposited by both wet and dry mechanisms. The type and abundance of base cations already present in an area is one aspect that dictates how acidic deposition will affect that environment. For example, because of its alkaline soils and bedrock, Alberta is less susceptible to acid deposition damage than is Eastern Canada (CASA, 1999). Western Canada, being generally an agricultural region, is dominated by soils rich in Ca^{2+} and Mg^{2+} (Gorham, 1976). The deposition of Ca^{2+}, Mg^{2+}, and K^+ generally originates from a combination of wind erosion of soils, agricultural tillage practices, and traffic on unpaved roads (Draaijers et al., 1997). Na^+, on the other hand, originates from sea spray, and is largely deposited in coastal areas (Draaijers et al., 1997).

This report presents an analysis of base cation deposition (wet, dry, and total) in western Canada, based on precipitation chemistry monitoring data. A technique for estimating surface-level air

concentrations of Na^+, Ca^{2+}, Mg^{2+}, and K^+, which was developed by Eder and Dennis (1991) using precipitation data from Ontario, was applied to precipitation monitoring stations in western Canada. The suitability of these relations to western Canada was tested using available direct measurements from two air monitoring stations in Alberta.

Wet, dry, and total deposition were plotted on maps of western North America, in order to examine the spatial variation of base cation deposition across the study area. Deposition values calculated for each station were gridded using kriging. Kriging is a geostatistical method that, by using weighted average interpolation algorithms, produces contour plots and attempts to express trends that are suggested in the data (Keckler, 1997). Kriging frequently gives a relatively accurate measure of the magnitude of missing values (DeMers, 1997). It interpolates the missing grid values based on the apparent spatial distribution of the available data.

2.0 DATA AND ANALYSIS METHODS

A spatial analysis of base cation deposition is examined by comparing both mean deposition and deposition trends among monitoring stations, using plots of western Canada. The main objective of this analysis is to estimate the pattern of base cation deposition in the study area.

2.1 Data Source

The study area consists of 31 monitoring stations in western Canada. These stations are located in the provinces of British Columbia, Alberta, and Saskatchewan, with four of the stations located in the United States (Washington and Montana). The 31 monitoring stations are shown in Figure 2.1. Precipitation chemistry data were taken from each of these stations. Table 2.1 gives the station names, the latitude and longitude coordinates for each station, and the period over which precipitation monitoring data were available. Also given in Table 2.1 are abbreviations for each station. These are used later in the report in order to save space on the spatial plots of base cation deposition.

Precipitation chemistry data from the 31 monitoring stations were obtained from the Canadian National Atmospheric Chemistry (NAtChem) Database, a system set up by Environment Canada's Atmospheric Environment Service as a central data base and analysis facility for determining the chemistry of regional-scale air and precipitation (EC, 1998). Data were collected from Canadian federal and provincial networks, as well as major U.S. networks. More information on NAtChem and how to obtain precipitation chemistry data sets can be found on the NAtChem website: http://arqm.tor.ec.gc.ca/natchem/main.html.

The data obtained for this study included monthly precipitation concentrations of Na^+, Ca^{2+}, Mg^{2+}, and K^+ during the 1982–1998 period. However, the periods of available data differed from station to station and ranged from 2 to 16 years in length (Table 2.1).

In addition to precipitation data, base cation air concentrations, measured directly from Beaverlodge and Esther, were obtained (respectively) from the Enforcement and Monitoring Division of Alberta Environment, using the Versatile Air Pollution Samplers (VAPS™), and from the Atmospheric and Hydrological Science Division of Environment Canada, Edmonton, using filter packs. These measured air concentrations were used for comparison with the concentrations that were estimated for Beaverlodge and Esther using the Eder and Dennis (1990) regression (section 2.3).

2.2 Wet Deposition

Wet deposition of base cations (Na^+, Ca^{2+}, Mg^{2+}, and K^+) was calculated from the precipitation chemistry data provided by NAtChem. Wet deposition values were calculated using the following equation:

$$\underset{\text{(kg/ha)}}{\text{Wet Deposition}} = \underset{\text{(mg/L)}}{\text{precip. conc.}} \times \underset{\text{(mm)}}{\text{precip. depth}} \Big/ 100 \qquad (1)$$

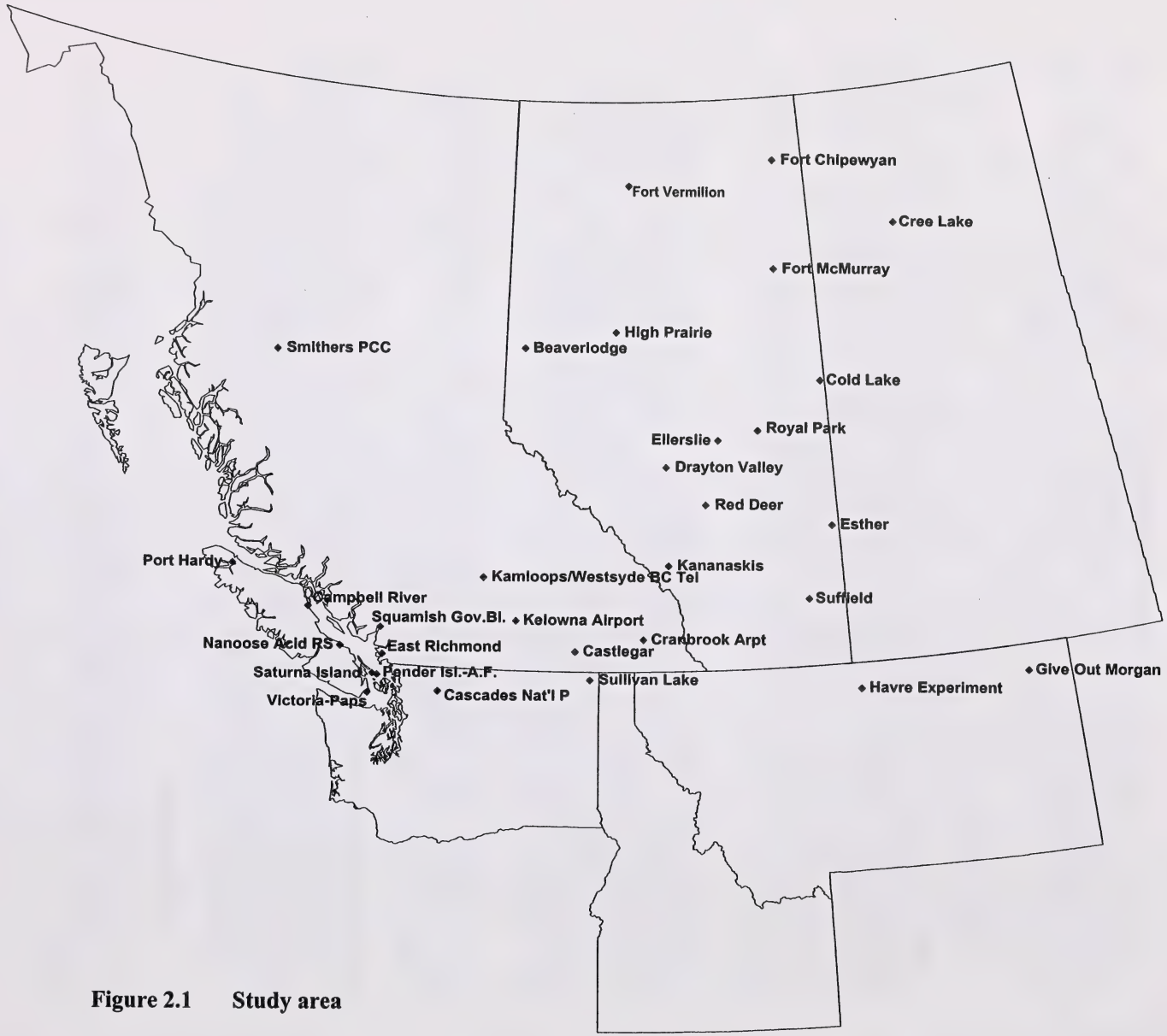


Figure 2.1 Study area

Table 2.1 Precipitation monitoring stations: abbreviations, locations, and record lengths

Station Name	Abbrev.	Latitude (degN)	Longitude (degW)	Data Available From	To
Alberta					
Beaverlodge	beav	55.2	119.4	1-Jan-88	3-Jan-96
Cold Lake	coldl	54.5	110.1	1-Jan-88	8-Jan-96
Drayton Valley	drayt	52.9	115.0	5-Jan-93	13-Dec-95
Ellerslie	eller	53.4	113.4	1-Jan-88	31-Dec-91
Esther	esth	51.7	110.2	1-Jan-87	1-Jan-99
Fort Chipewyan	ftch	58.8	111.0	1-Jan-89	29-Sep-95
Fort McMurray B	ftmc	56.7	111.3	1-Jan-88	2-Jan-96
Fort Vermillion	ftver	58.4	116.1	1-Jan-88	29-Nov-95
High Prairie	highp	55.5	116.5	1-Jan-88	30-Sep-95
Kananaskis	kana	51.0	115.0	1-Jan-88	10-Jan-96
Red Deer	redd	52.2	113.9	1-Jan-88	3-Jan-96
Royal Park	royal	53.6	112.2	1-Jan-92	3-Jan-96
Suffield	suff	50.3	111.0	1-Jan-88	10-Jan-96
British Columbia					
Campbell River	camp	50.0	125.2	1-Jan-94	31-Dec-96
Castlegar	castl	49.4	117.7	1-Jan-93	2-Jan-97
Cranbrook Airport	cranb	49.6	115.8	1-Jan-89	31-Dec-90
East Richmond	erich	49.2	123.0	1-Jan-89	31-Dec-92
Kamloops Westsyde BC Tel	kamwes	50.8	120.3	1-Jan-89	31-Dec-94
Kelowna Airport	kelow	50.0	119.4	1-Jan-89	31-Dec-94
Nanoose Acid RS	nanoo	49.3	124.2	1-Jan-89	31-Dec-95
Pender Isl.-A.F.	pend	48.8	123.3	1-Jan-89	31-Dec-90
Port Hardy	porth	50.6	127.5	1-Jan-89	31-Dec-94
Saturna Island	satur	48.8	123.1	1-Jan-89	31-Dec-94
Smithers PCC	smith	54.8	127.2	1-Jan-89	31-Dec-90
Squamish Gov.Bl.	squam	49.7	123.2	1-Jan-89	31-Dec-96
Victoria - Paps	vict	48.4	123.4	1-Jan-89	31-Dec-96
Saskatchewan					
Cree Lake	creel	57.4	107.1	1-Jan-83	31-Dec-93
Montana					
Give Out Morgan	giveo	48.5	105.2	1-Jan-82	30-Dec-97
Havre Experiment	havre	48.5	109.8	1-Jan-85	30-Dec-97
Washington					
Cascades Nat'l P	casc	48.5	121.4	1-Jan-84	30-Dec-97
Sullivan Lake	sulli	48.8	117.3	1-Jan-84	31-Dec-87

The monthly wet deposition values calculated for each station were summed to give annual wet deposition values in kg/ha and keq/ha. The annual wet deposition values were then averaged to give a mean annual value for each station.

Annual trends in wet deposition were also computed for each station using a simple linear regression analysis and best-fit line approximation. A statistical analysis was then performed, including the calculation of variation in both mean annual precipitation concentrations and annual wet deposition from year to year, as well as standard deviation of annual wet deposition over the data period. The wet deposition trends were tested for statistical significance at the 1% and 5% levels.

2.3 Dry Deposition

Air concentrations of base cations are not measured as extensively as wet deposition (Cheng et al., 1997). As a result, air concentrations were estimated using the scavenging ratio, a technique developed by Eder and Dennis (1990), which estimates surface-level air concentrations of Na^+, Ca^{2+}, Mg^{2+}, and K^+ from precipitation concentrations. Eder and Dennis used measurements of base cation concentrations in precipitation and in ground-level air at 23 Ontario sites to derive these scavenging ratios. Four relations, one for each cation, were developed (Table 2.2) based on the linear relationship between measured surface-level air and precipitation concentrations. This inference technique is based on the idea that precipitation efficiently scavenges alkaline aerosols, resulting in a strong correlation between precipitation concentrations and air concentrations at the surface (Eder and Dennis, 1990).

Table 2.2 Eder-Dennis (Ontario) linear regression equations

Cation	*Linear Regression Equations**	*Correlation*
Na+	Air conc. = 1.600(Prec. conc.) + 0.018	0.82
Ca2+	Air conc. = 2.149(Prec. conc.) - 0.280	0.93
Mg2+	Air conc. = 1.569(Prec. conc.) + 0.002	0.95
K+	Air conc. = 1.107(Prec. conc.) + 0.0426	0.51

* From Eder and Dennis (1990)

For simplicity, these linear regression equations, derived from Ontario data by Eder and Dennis (1990) are referred to as the 'Ontario regression' in this report.

The air concentrations of cations estimated by the Eder-Dennis (Ontario) regression were compared to directly measured concentrations at Beaverlodge and Esther to evaluate how well the Ontario regression approximates base cation concentrations in western Canada. The measured air concentrations at Beaverlodge and Esther were then used to perform a new regression, and derive a set of four equations to be used in western Canada as an alternative to the Ontario equations. These relationships, based on data from Beaverlodge and Esther, Alberta, are referred to as the 'Alberta regression' in this report.

The base cation air concentrations calculated from both sets of equations were used to estimate dry deposition at each station. The dry deposition flux was calculated as the product of dry deposition velocity (V_d) and ground-level air concentration, according to the following equation:

$$\underset{(kg/m^2s)}{\text{Dry Deposition Flux}} = \underset{(kg/m^2)}{\text{air conc.}} \times \underset{(m/s)}{V_d} \qquad (2)$$

The deposition velocity characterizes dry deposition, it is a proportionality constant that relates the amount of the species deposited per unit area per second (the deposition flux) to the air concentration (Finlayson-Pitts and Pitts, 2000). The deposition velocity is the speed at which substances (either as gases or attached to particles) are deposited on surfaces (leaves, water bodies, soils) (Target Loading Subgroup, 1999). Deposition velocities have been determined for each of the base cations, however, it is becoming recognized that deposition velocities change with environmental conditions (Hofschreuder et al., 1997; Ruijgrok et al., 1997; Wyers and Duyzer, 1997; cited in Target Loading Subgroup, 1999). Because of the large variation in deposition velocities, a typical deposition velocity of 0.0100 m/s, as suggested by Eder and Dennis (1990), was used for all cations in this study.

Annual dry deposition was calculated by first calculating the average dry deposition flux (as given by equation (2) above) using an annual average air concentration. This dry deposition flux (in kg/m^2s) was then multiplied by the number of seconds in one year, and the necessary unit conversions were made to give annual dry deposition in kg/ha and keq/ha.

2.4 Total Deposition

Total deposition (wet plus dry) of base cations was calculated for each station in the study area according to the following equation:

$$\underset{(keq/ha)}{\text{Total Deposition}} = \underset{(keq/ha)}{\text{Wet Deposition}} + \underset{(keq/ha)}{\text{Dry Deposition}} \qquad (3)$$

Total deposition was calculated annually, as well as over the entire data period for each station. Mean annual total deposition values were used for comparison since each station has a different data period. Annual total deposition trends, in keq/ha/y, were also calculated

3.0 WET DEPOSITION

The following section examines the precipitation concentrations of base cations Na^+, Ca^{2+}, Mg^{2+}, and K^+ and investigates mean annual wet deposition as well as wet deposition trends at each of the stations in the study area.

3.1 Precipitation Concentrations

Precipitation concentrations measured at the 31 monitoring stations in the study area were used to calculate wet deposition and to estimate dry deposition. The coefficient of variation was calculated for the average precipitation concentrations of each cation and for total base cations. In section 3.4, the coefficient of variation for annual wet deposition was calculated in the same manner.

The coefficient of variation is defined as the sample standard deviation expressed as a percentage of the sample mean (Steel and Torrie, 1980), and is a relative measure of variation. In this case the coefficient of variation describes the amount of dispersion in precipitation concentrations over the years of data at the different monitoring stations, relative to a typical precipitation concentration value (the mean for each station).

As seen in Figure 3.1, most variation coefficients were between 21 and 40% for average base cation precipitation concentrations. The least variation was seen in Mg^{2+} precipitation concentrations, and the most variation was seen in Ca^{2+} and K^+ precipitation concentrations. Table AI.1 (in the appendix) gives the coefficient of variation for average precipitation concentrations, over the years of data available at each station. Table AI.1 shows that the base cation precipitation concentrations in western Canada are quite variable.

The station with the greatest variation in precipitation concentrations was Give Out Morgan, in Montana, with a coefficient of variation of 131% for total base cations. The station with the lowest coefficient of variation for base cation concentrations was Cranbrook Airport in British Columbia, where the coefficient of variation was 5%, based on only two years of data.

3.2 Mean Annual Wet Deposition

Wet deposition was calculated using precipitation concentrations of base cations and precipitation depth, according to equation (1). A plot of mean annual precipitation depth is given in Figure AI.1 in the appendix. The large amount of variation in precipitation depth in the BC coastal area seems questionable. This is most likely a combined result of the differing lengths in data periods between stations (for example the stations with only two years of data) and some years having more rain than others (1993, for example).

Table 3.1 shows mean annual wet deposition (in keq/ha) for individual base cations and total base cations at each station in the study area. Stations are listed using the abbreviations given in Table 2.1. Wet deposition of other ions (including H^+, SO_4^{2-}, XSO_4^{2-} [excess sulphate content], NO_3^-, Cl^-, and NH_4^+) was also calculated from the existing data to examine the total precipitation chemistry. The annual wet deposition values for these additional ions are given in Table AI.2 in the appendix.

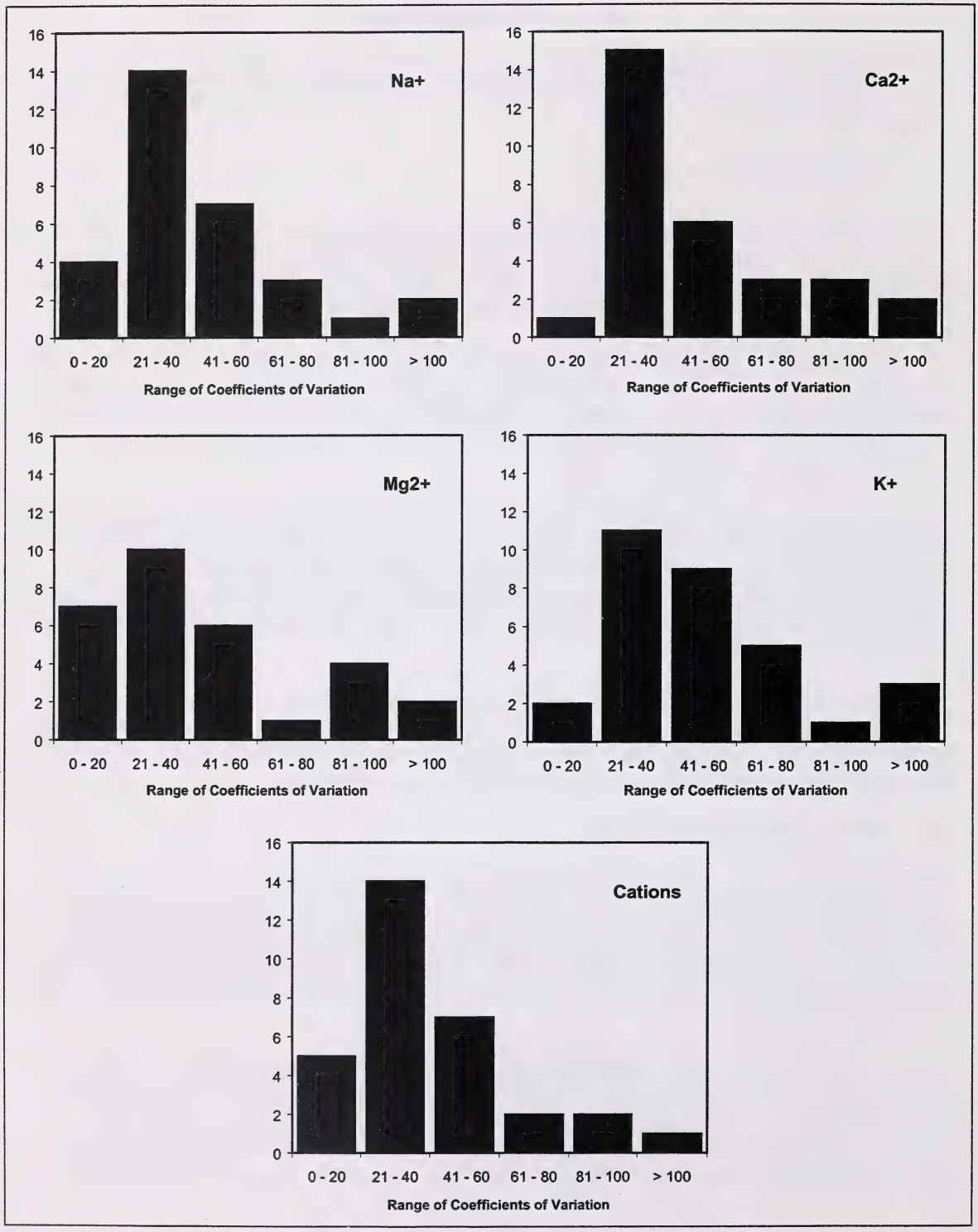


Figure 3.1 **Distribution of variation coefficients for average precipitation concentrations**

Table 3.1 Average annual wet deposition (keq/ha)

Station	Years	*Na*	*Ca*	*Mg*	*K*	*Cations*
beav	*88 - 95*	0.007	0.025	0.006	0.005	0.042
coldl	*88 - 95*	0.011	0.043	0.016	0.007	0.079
drayt	*93 - 95*	0.009	0.080	0.022	0.014	0.126
eller	*88 - 91*	0.008	0.048	0.012	0.004	0.073
esth	*87 - 98*	0.005	0.026	0.010	0.002	0.043
ftch	*89 - 95*	0.018	0.045	0.012	0.010	0.085
ftmc	*88 - 95*	0.008	0.035	0.016	0.003	0.062
ftver	*88 - 95*	0.005	0.026	0.006	0.004	0.042
highp	*88 - 95*	0.009	0.117	0.026	0.020	0.172
kana	*88 - 95*	0.008	0.077	0.025	0.004	0.113
redd	*88 - 95*	0.005	0.055	0.015	0.003	0.078
royal	*92 - 95*	0.010	0.069	0.019	0.004	0.102
suff	*88 - 95*	0.020	0.067	0.026	0.007	0.120
camp	*94 - 96*	0.203	0.038	0.056	0.018	0.253
castl	*93 - 96*	0.029	0.030	0.006	0.013	0.077
cranb	*89 - 90*	0.010	0.032	0.019	0.004	0.065
erich	*89 - 92*	0.167	0.138	0.040	0.023	0.369
kamwes	*89 - 94*	0.011	0.017	0.004	0.006	0.037
kelow	*89 - 94*	0.019	0.022	0.005	0.010	0.056
nanoo	*89 - 95*	0.070	0.033	0.016	0.020	0.133
pend	*89 - 90*	0.087	0.020	0.019	0.009	0.136
porth	*89 - 94*	0.745	0.063	0.151	0.050	1.009
satur	*89 - 94*	0.179	0.024	0.038	0.015	0.256
smith	*89 - 90*	0.019	0.054	0.010	0.010	0.093
squam	*89 - 96*	0.115	0.045	0.024	0.024	0.199
vict	*89 - 96*	0.153	0.027	0.031	0.012	0.216
creel	*83 - 93*	0.004	0.017	0.006	0.002	0.030
casc	*84 - 97*	0.107	0.023	0.030	0.005	0.165
giveo	*82 - 97*	0.009	0.030	0.013	0.003	0.054
havre	*85 - 97*	0.007	0.017	0.006	0.002	0.032
sulli	*84 - 87*	0.010	0.026	0.007	0.003	0.046

Na^+ and Ca^{2+} had the highest mean annual wet deposition values of all cations, and this was observed in British Columbia. Figure 3.2 illustrates the mean annual wet deposition across the study area for the four cations. The largest wet deposition value was for Na^+ at Port Hardy in western BC, where the mean annual wet deposition over the 1989–1994 period was 0.745 keq/ha. This is consistent with the BC coast being subject to sea spray, which releases Na.

The cation with the lowest mean annual wet deposition, on average, was K^+. For all cations but Ca^{2+}, wet deposition values were highest in western BC and decreased to the east of the study area. In the case of Ca^{2+}, which generally originates from soil dust, wet deposition concentrations were high in both central Alberta and in southwestern BC, with concentrations decreasing with distance from these points.

For total base cations, mean annual wet deposition ranged from 0.030 to 1.009 keq/ha at the precipitation monitoring stations across western Canada. Figure 3.3 is a plot of mean annual wet deposition for total base cations at each station. The greatest mean annual wet deposition for total base cations occurred in western BC, with the highest value at Port Hardy (1.009 keq/ha). As shown in Figure 3.3, another peak in base cation wet deposition was observed at High Prairie, Alberta, where the mean annual wet deposition was 0.172 keq/ha.

3.3 Wet Deposition Trends

Annual base cation wet deposition trends were generally decreasing at the stations over time. This is consistent with the findings of Hedin et al. (1994), who report that atmospheric concentrations of base cations have declined over the past 10–26 years in North America. Wet deposition of base cations decreased at 18 of the 31 stations over the 1982–1998 period. Table 3.2 gives the annual wet deposition trends (in keq/ha/y) for each individual cation and for total base cations. The most substantial decrease in wet deposition occurred at Port Hardy, BC, where the annual trend in wet deposition over the 1989–1994 period was -0.068 keq/ha/y. In order to give the total precipitation chemistry, the wet deposition trends of additional ions are given in Table AI.3 in the appendix.

One station, Campbell River, BC, had a large increasing trend in annual wet deposition of base cations, 0.098 keq/ha/y over the 1994–1996 period. However, Ca^{2+} and Mg^{2+} were only measured during 1996 at this station. Of the 31 stations in the study area, only 7 had annual wet deposition trends that were significant at the 5% level: Drayton Valley, Kananaskis, Campbell River, Cranbrook Airport, Pender Isl., Smithers PCC, and Squamish Gov. Bl. The trends at Cranbrook Airport, Pender Isl., and Smithers PCC were based on only two years of data. Figure 3.4 shows the spatial variation in wet deposition trends of base cations. The trend value is given below the station abbreviation, and those trends that are significant at the 5% level are marked by an asterisk.

3.4 Wet Deposition Variability

The standard deviation in annual wet deposition of all base cations ranged from 0.005 to 0.5 keq/ha at the 31 monitoring stations in the study area. In general, the greatest standard deviation was seen for annual wet deposition of Na^+ and Ca^{2+}. Standard deviation values for annual wet deposition are given in Table AI.4, in the appendix.

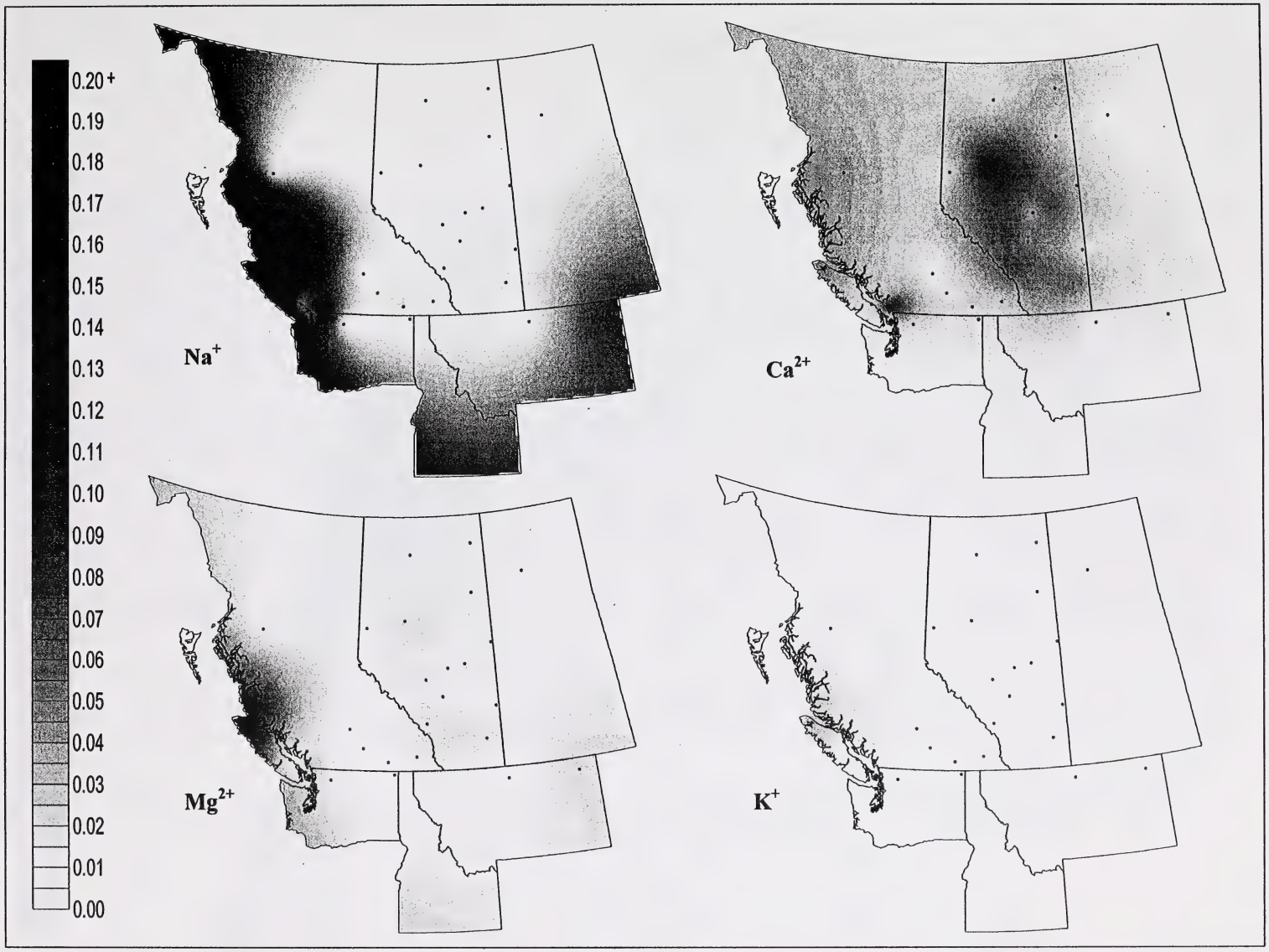
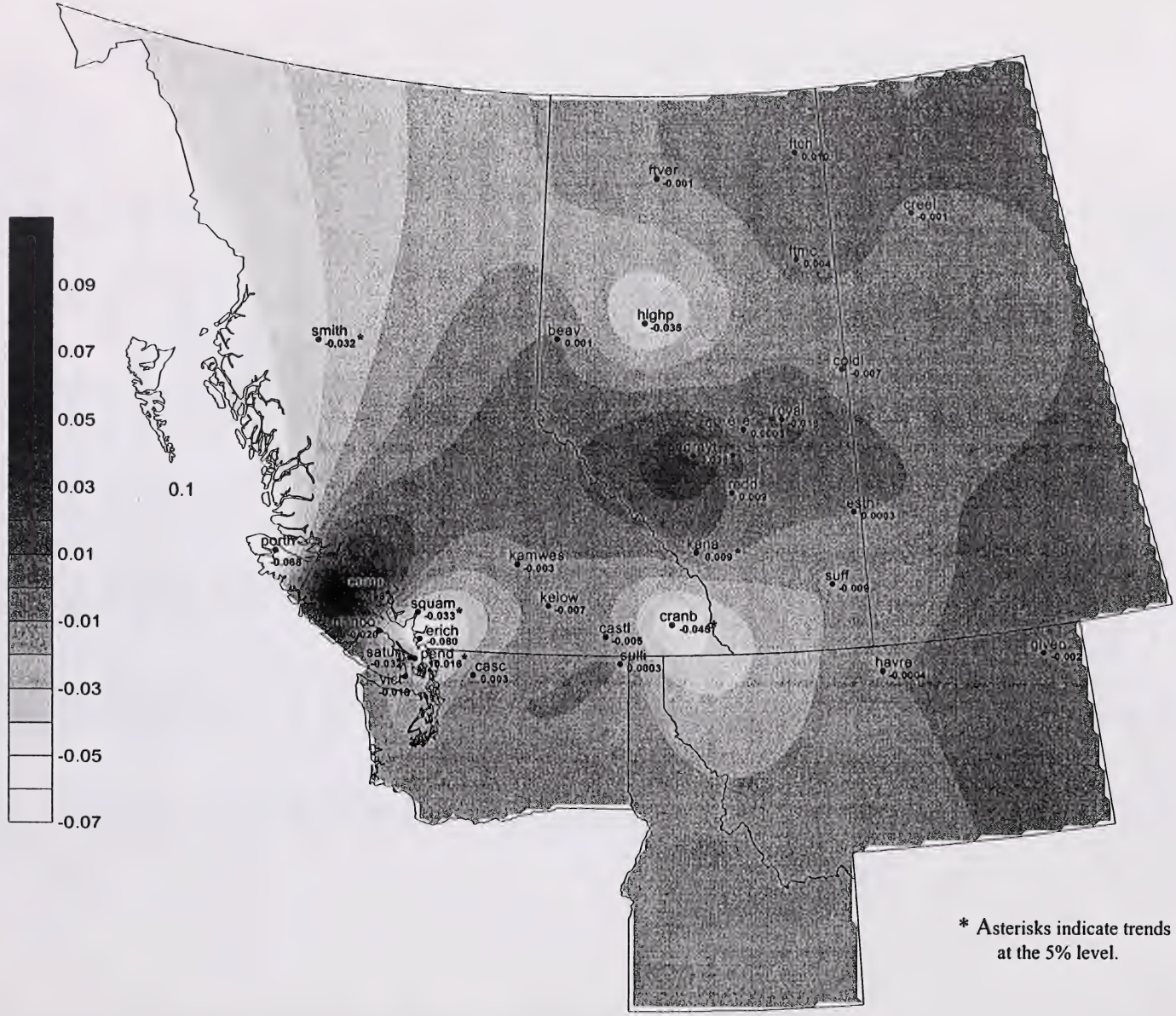


Figure 3.2 Mean annual wet deposition (keq/ha) of Na^+, Ca^{2+}, Mg^{2+}, and K^+

Figure 3.3 Mean annual wet deposition of all base cations (keq/ha)

Table 3.2 Annual wet deposition trends (keq/ha/y)

Station	Years	Na	Ca	Mg	K	Cations
beav	88 - 95	-0.001	0.002	0.0002	-0.0001	0.001
coldl	88 - 95	-0.003	-0.002	-0.001	-0.001	-0.007
drayt	93 - 95	-0.002	0.024	0.008	0.006	0.036
eller	88 - 91	0.0005	-0.0004	-0.0002	0.0003	0.0002
esth	87 - 98	-0.0002	0.0002	0.0003	0	0.0003
ftch	89 - 95	0.002	0.007	0.002	-0.0001	0.010
ftmc	88 - 95	-0.0004	0.003	0.0005	0.0003	0.004
ftver	88 - 95	-0.0001	-0.0003	-0.0005	-0.0003	-0.001
highp	88 - 95	-0.002	-0.021	-0.006	-0.005	-0.035
kana	88 - 95	-0.001	0.009	0.001	0	0.009
redd	88 - 95	-0.0003	0.008	0.001	-0.0005	0.009
royal	92 - 95	-0.0004	0.013	0.003	0.0003	0.016
suff	88 - 95	-0.003	-0.004	-0.002	-0.001	-0.009
camp	94 - 96	0.042			0.009	0.098
castl	93 - 96	-0.005	-0.0005	0.001	-0.0005	-0.005
cranb	89 - 90	-0.005	-0.025	-0.015	-0.0001	-0.045
erich	89 - 92	-0.039	-0.027	-0.008	-0.005	-0.080
kamwes	89 - 94	-0.0003	-0.002	-0.0004	-0.0004	-0.003
kelow	89 - 94	-0.003	-0.001	-0.0003	-0.002	-0.007
nanoo	89 - 95	-0.012	-0.0003	-0.001	-0.002	-0.020
pend	89 - 90	0.015	-0.004	0.009	-0.004	0.016
porth	89 - 94	-0.054	-0.001	-0.010	-0.003	-0.068
satur	89 - 94	-0.025	-0.0003	-0.005	-0.001	-0.032
smith	89 - 90	-0.002	-0.026	-0.003	-0.001	-0.032
squam	89 - 96	-0.012	-0.012	-0.006	-0.003	-0.033
vict	89 - 96	-0.007	-0.004	-0.002	-0.002	-0.018
creel	83 - 93	-0.0004	-0.001	-0.0001	0	-0.001
casc	84 - 97	0.004	-0.0002	-0.001	0.0001	0.003
giveo	82 - 97	0.0001	-0.002	-0.0003	0	-0.002
havre	85 - 97	0	-0.0002	-0.0002	0	-0.0004
sulli	84 - 87	0.002	-0.0003	-0.001	0	0.0003



* Asterisks indicate trends significant at the 5% level.

Figure 3.4 **Trends in mean annual wet deposition of base cations (keq/ha/y)**

The coefficient of variation was also investigated for annual wet deposition in order to determine how the wet deposition of each base cation and total base cations varied from year to year at each station. The greatest variations in wet deposition were seen at High Prairie, Castlegar, Squamish Gov. Bl., and Give Out Morgan, for Ca^{2+} and Mg^{2+}. The coefficients of variation are given for each station in Table AI.5 in the appendix.

The station with the greatest variation in annual wet deposition of base cations was High Prairie, where the coefficient of variation was 134% over the 1988–1995 period. The least variation in annual wet deposition occurred at Pender Isl., where the coefficient of variation was 8% over the 1989–1990 period. Figure 3.5 shows the distribution of variation coefficients for wet deposition of Na^{+}, Ca^{2+}, Mg^{2+}, K^{+}, and total base cations. Most variation coefficients for wet deposition were in the range of 21–60%, suggesting that wet deposition values are quite variable from year to year in western Canada.

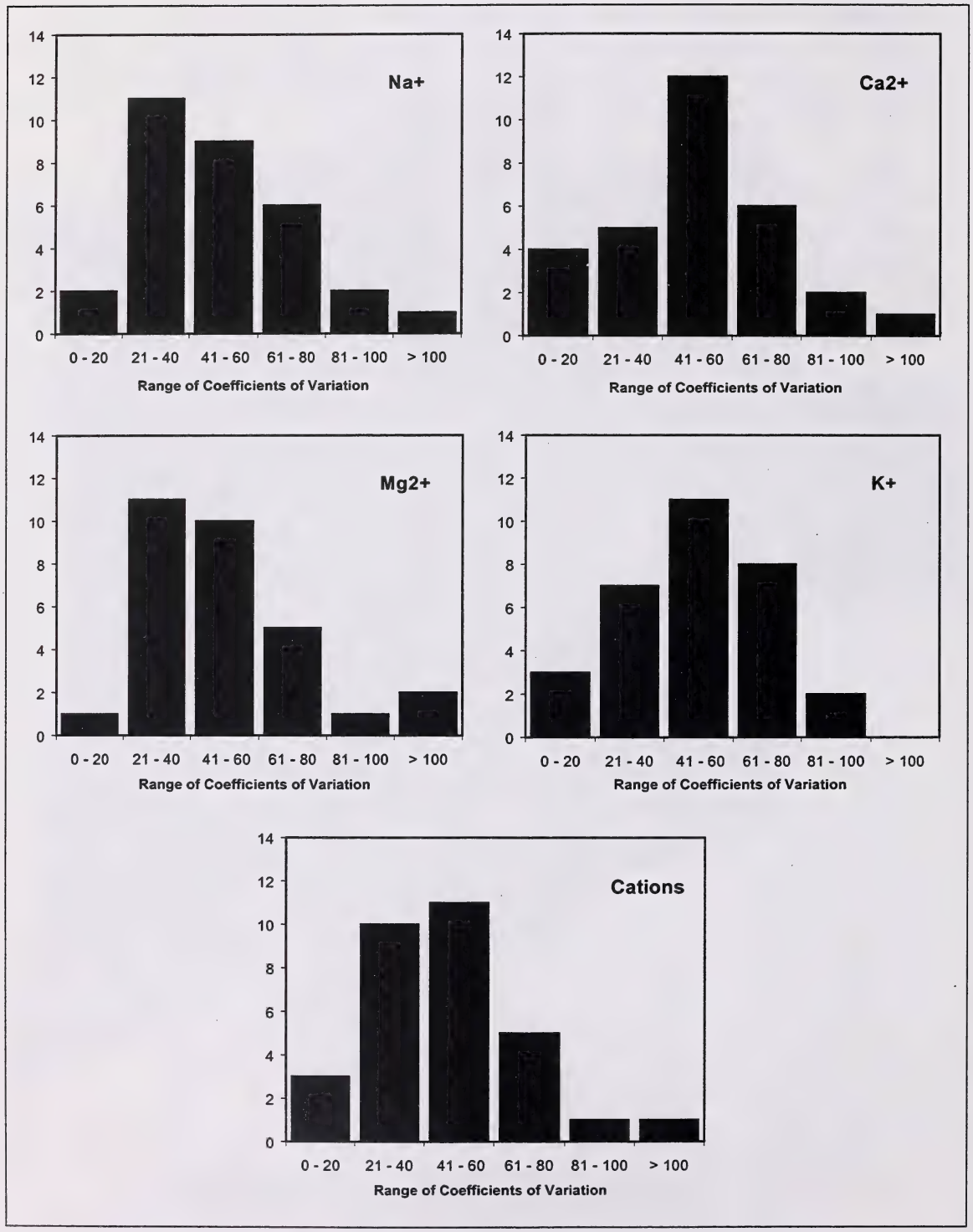


Figure 3.5 Distribution of variation coefficients for annual wet deposition

4.0 DRY DEPOSITION

This section discusses the calculation of base cation air concentrations by two estimation methods, the Ontario (Eder-Dennis) regression and the Alberta regression. Dry deposition of base cations is also examined, based on the air concentrations estimated by each regression.

4.1 Air Concentrations

Air concentrations were first approximated using equations from the Ontario (Eder-Dennis) regression, given in Table 2.2. The air concentrations calculated by this method were compared to the only available direct measurements in the study area, which were at Beaverlodge and Esther, Alberta. Air concentrations were also estimated using equations from a regression of Beaverlodge and Esther data, which are referred to as the 'Alberta regression' in this report. The air concentrations estimated by both regressions were compared and then used to calculate dry deposition for each station in the study area.

4.1.1 Estimates Using Eder-Dennis Equations

Air concentrations estimated using the Ontario regression differed from the air concentrations actually measured at Esther and Beaverlodge. In fact, the Ontario equation for Ca^{2+} gave negative air concentrations at some stations.

When estimating air concentrations of Ca^{2+}, the Eder-Dennis equation gave negative values for 12 of the 31 stations in the study area. The Eder-Dennis equation for Ca^{2+} has a negative y-intercept, indicating that when there is no Ca^{2+} in the precipitation, there is a negative concentration in the air. In reality, of course, it is not possible to have negative air concentrations, as there are always some base cations in the atmosphere.

A simple reason for the discrepancy noted above is likely that the Eder-Dennis equations are based on Ontario data, and base cation conditions are different in western Canada. Alberta is drier and has more dust, which is a source of Ca^{2+} (Cheng et al., 1997; Finlayson-Pitts and Pitts, 2000). In addition, the analysis carried out by Eder and Dennis (1990) was concerned with the long-range transport of particles. Storm systems transport base cations north from the U.S. in precipitation, violating the mass balance within Ontario. Therefore, scavenging ratios are not solely dependent on local air. In order to alleviate this problem for application of the scavenging ratio to western Canada, the regression equation for Ca^{2+} air concentrations was modified when needed, so that some Ca^{2+} concentrations were calculated using a 'modified Ontario regression'.

In order to get rid of negative Ca^{2+} air concentrations, the slope of the Eder-Dennis equation for Ca^{2+} was forced through zero. To accomplish this, any positive Ca^{2+} values estimated by the original Ontario (Eder-Dennis) regression were plotted against precipitation concentrations, and the y-intercept was set to zero. In this way, zero is added as a point so that negative no values will result. The resulting modified equation was used to replace any negative Ca^{2+} values. Table 4.1 lists the stations that had negative Ca^{2+} values using the original Ontario regression, and gives the modified equation used for that station.

Table 4.1 Stations where negative Ca^{2+} concentrations were calculated using the Eder-Dennis (Ontario) equations

Station	*Yrs with -ve Ca^{2+} Conc's*	*Replacement Equation*	*Notes*
Beaverlodge	89-92 out of 88-95	y = 1.1432x	
Fort Chipewyan	89+90 out of 89-95	y = 1.8177x	
Fort Vermilion	90 out of 88-95	y = 1.7837x	
Campbell River	96 out of 94-96	y = 0.4796x	- used Nanoose Acid RS data (91-94)
Pender Isl. -A.F.	89 out of 89-90	y = 0.7164x	
Port Hardy	89-91+ 93 out of 89-94	y = 0.4085x	
Saturna Island	89-92 out of 89-94	y = 0.5137x	
Squamish Gov.	92, 94, 96 out of 89-96	y = 0.4796x	
Cree Lake	85-87+ 92-83 out of 83-93	y = 1.1283x	
Cascades Nat'l P	84-97, all years	y = 1.1351x	- used Sullivan Lake data (84-87)
Give Out Morgan	89, 96, 97 out of 82-97	y = 1.9686x	
Havre Experiment	89, 96, 97 out of 85-97	y = 1.0956x	

The estimated base cation air concentrations were compared to directly measured concentrations of Ca^{2+} at Beaverlodge, Alberta over the 1997–1999 period. The air concentrations estimated for Beaverlodge were larger than the concentrations directly measured at the monitoring station over all three years, except in the case of Ca^{2+}. In 1997 and 1999, the measured air concentrations of Ca^{2+} were higher than the concentrations estimated by the Ontario regression. However, some Ca^{2+} air concentrations were estimated for Beaverlodge using a modified version of the Eder-Dennis regression equation (Table 4.1) in order to get rid of negative concentrations. The magnitudes of calculated air concentrations and directly measured concentrations are compared in Figure 4.1. On average, the calculated air concentrations were 1.8 times greater than the concentrations measured at Beaverlodge.

Similar to what was found for Beaverlodge, the estimated air concentrations at Esther over the 1991–1998 period were greater than the air concentrations measured directly at Esther, for all cations and all eight years of data (Figure 4.2). On average, the air concentrations calculated for Esther by the Ontario regression were 4.9 times greater than the concentrations measured directly at the station. In comparison, air concentrations estimated by the Ontario regression were more comparable for Beaverlodge than for Esther.

Overall, the Ontario equations derived by Eder and Dennis for estimating base cation air concentrations are not suitable for western Canada. The most probable explanation for the failure of the Eder-Dennis equations in estimating base cation air concentrations in western Canada is the difference in conditions between the two areas. Ontario is not as dry and dusty as western Canada, and Ontario is influenced by long-range transport of base cations from the United States. Other climatic differences between the two areas may also play a role in rain formation and, consequently, affect the washout of base cations is in each respective area.

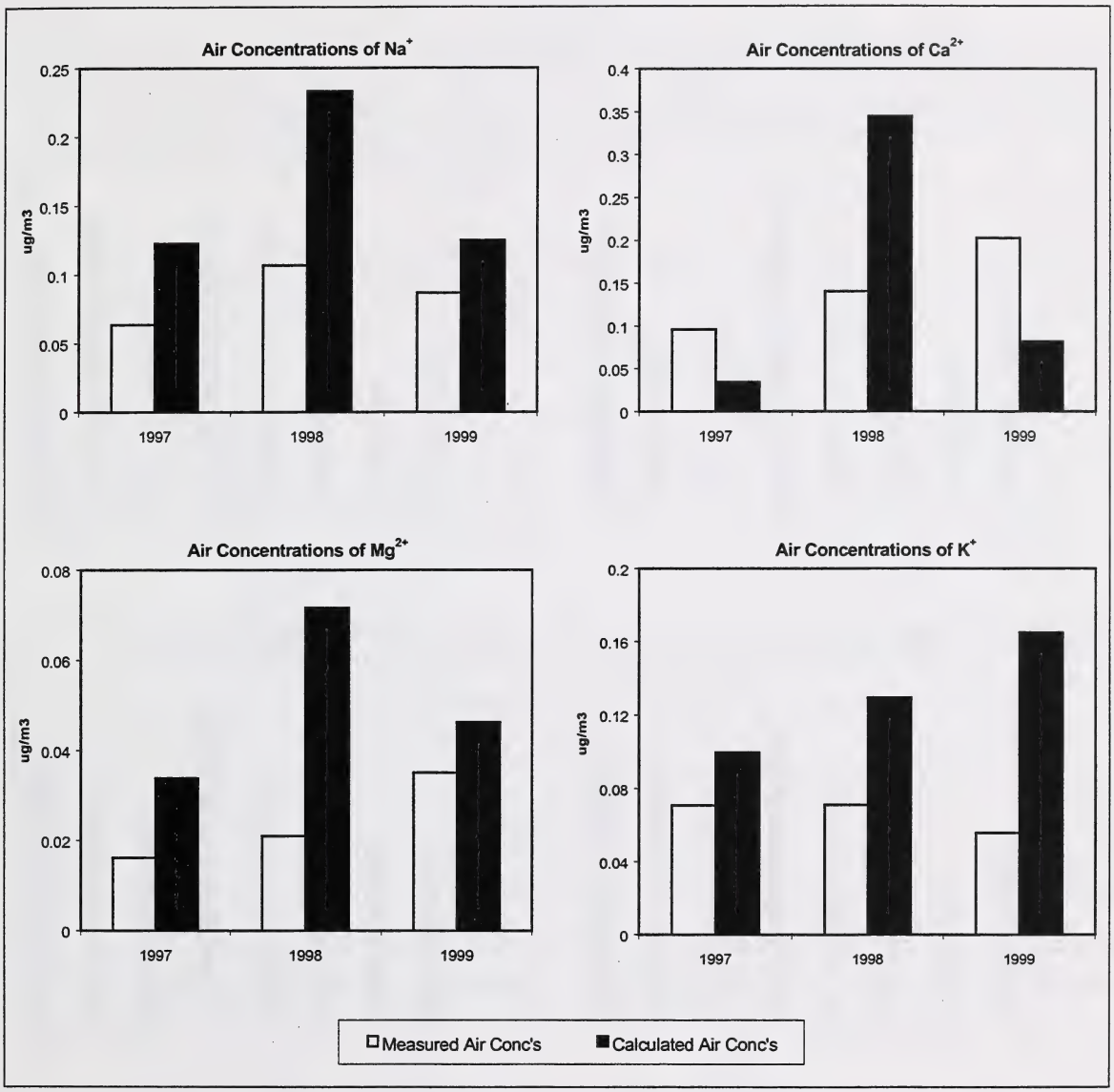


Figure 4.1 Comparison of air concentrations measured at Beaverlodge to those calculated using the Ontario (Eder-Dennis) regression

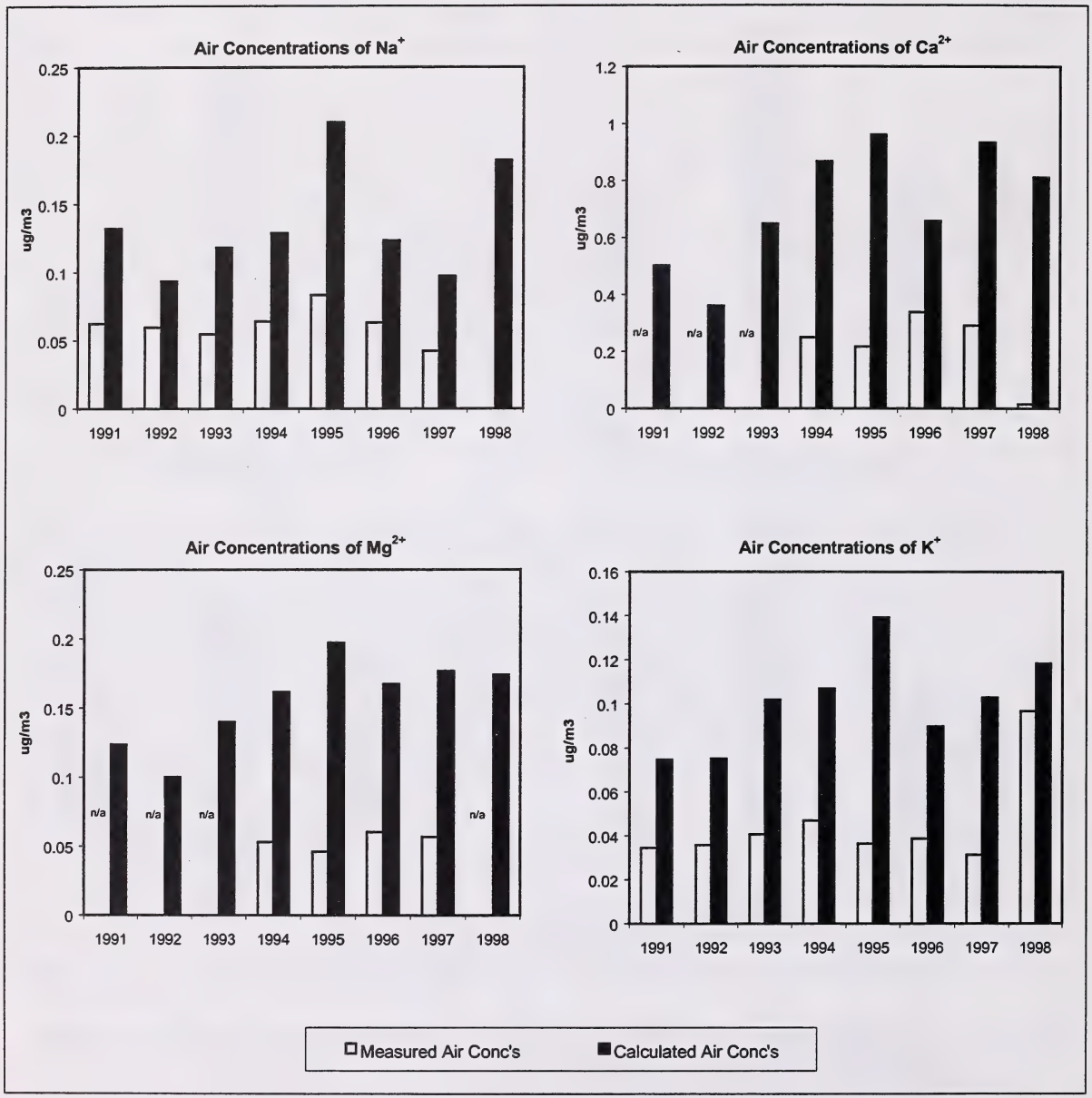


Figure 4.2 Comparison of air concentrations measured at Esther to those calculated using the Ontario (Eder-Dennis) regression

4.1.2 Estimates Using Relationships from Beaverlodge and Esther Data

Mean annual air concentrations and mean precipitation concentrations from Beaverlodge and Esther, Alberta were plotted for each cation (Figure 4.3). These data were collected from the two stations over the 1991–1999 period. As Figure 4.3 shows, a best-fit straight line was drawn through the points to give the approximate linear relationship between the points. Table 4.2 lists the equations and the correlation value for each relation.

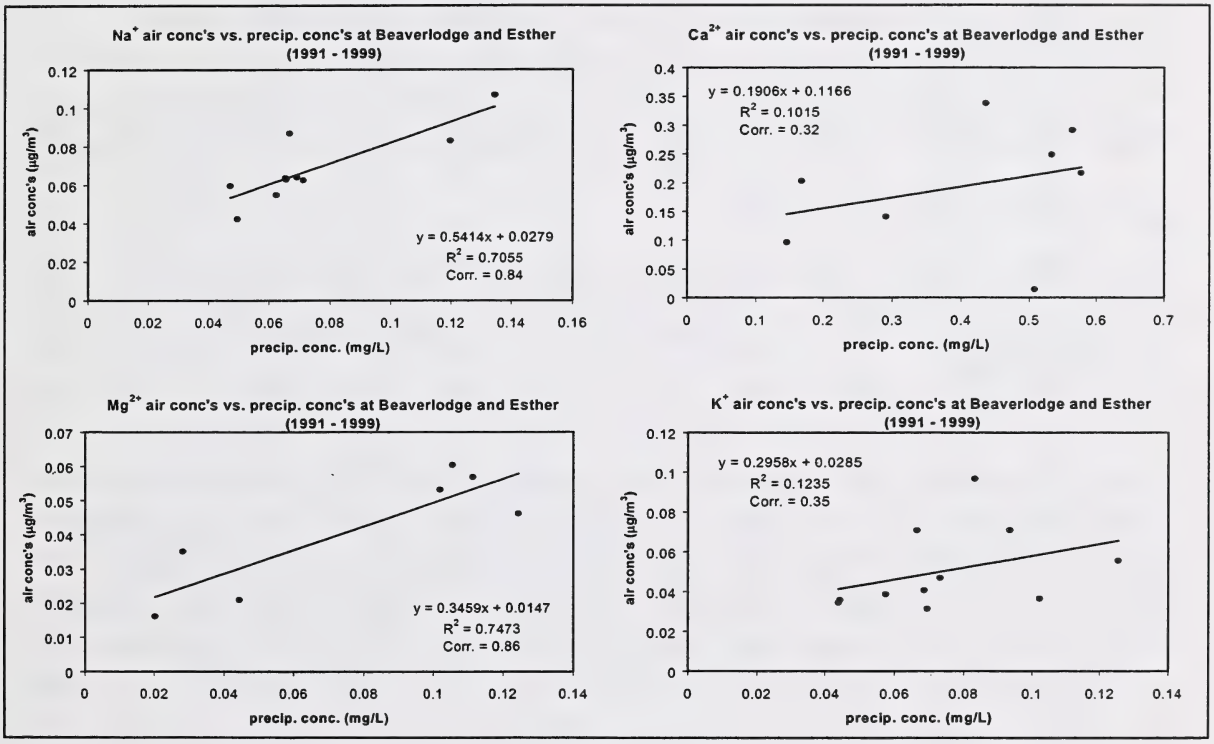


Figure 4.3 Scatter plots of base cation precipitation and surface-level air concentrations in Alberta

Table 4.2 Alberta (Beaverlodge and Esther) linear regression equations

Cation	*Linear Regression Equations*	*Correlation*
Na+	Air conc. = 0.5414(Prec. conc.) + 0.0279	0.84
Ca2+	Air conc. = 0.1906(Prec. conc.) + 0.1166	0.32
Mg2+	Air conc. = 0.3459(Prec. conc.) + 0.0147	0.86
K+	Air conc. = 0.2958(Prec. conc.) + 0.0285	0.35

These linear regression equations, derived from base cation measurements at the Beaverlodge and Esther stations, give an alternative to the Ontario regression equations. However, a conclusion cannot be made as to whether this Alberta regression is more suitable than the Ontario regression for the whole of western Canada. More monitoring is required in western Canada in order to make this comparison since no stations besides Beaverlodge and Esther measure base cation air concentrations in the western Canada study area. With more data, it could be determined if station-specific equations are needed, or if a regional set of equations would be sufficient for approximating base cation air concentrations.

The Alberta regression equations (Table 4.2) are quite different from the Ontario regression equations (Table 2.2). The slopes of the Alberta equations are smaller than the Ontario slopes (for Ca^{2+} in particular), and all y-intercepts are positive for the Alberta equations. The correlation coefficients are greater for the Ontario regression equations than for the Alberta equations, but more data were available in Ontario. The K^{+} correlation coefficient, however, is low for both regressions.

4.2 Mean Annual Dry Deposition

Dry deposition values were calculated using air concentrations from both the Ontario and the Alberta regressions. The results of these two methods are compared, as is dry deposition, among all the stations in the study area. A comparison is also made between the magnitudes of wet deposition and dry deposition.

4.2.1 Estimates Using Eder-Dennis Equations

Using air concentrations estimated by the Ontario regression, mean annual dry deposition values for base cations ranged from 0.058 to 0.682 keq/ha for western Canada. Table 4.3 gives mean annual dry deposition (in keq/ha) and annual dry deposition trends (in keq/ha/y) for each individual cation and for total base cations. The greatest mean annual dry deposition value was estimated at the Smithers PCC station, located in western BC. Mean annual dry deposition minima were estimated at Cree Lake, Saskatchewan and Cascades Nat'l Park, Washington. Figure 4.4 is a plot of the mean annual dry deposition of all base cations in the study area, based on the Ontario regression.

Overall, mean annual dry deposition values, estimated using the Ontario regression, were higher than the mean annual wet deposition values of base cations in western Canada. This is contrary to the findings of other studies (Summers, 1987; Samara and Tsitouridou, 2000), which showed that wet deposition most often exceeds dry deposition (in western Canada and Greece, respectively). A plot of the ratio of dry-to-wet deposition is given in Figure AI.2 in the appendix.

4.2.2 Estimates Using Relationships from Beaverlodge and Esther Data

Mean annual dry deposition values, based on the Alberta regression equations, ranged from 0.042 to 0.140 keq/ha over western Canada. Table 4.4 gives mean annual dry deposition values (in keq/ha) and annual dry deposition trends (in keq/ha/y) for each cation and for total base cations, based on air concentrations estimated with the Alberta regression. The greatest mean annual dry deposition was estimated at Port Hardy (0.140 keq/ha) in western BC.

Table 4.3 Mean annual dry deposition and annual dry deposition trends, using Ontario regression

		Mean Annual Dry Deposition (keq/ha)					*Annual Dry Deposition Trends (keq/ha/yr)*				
Station	**Years**	*Na*	*Ca*	*Mg*	*K*	*Cations*	*Na*	*Ca*	*Mg*	*K*	*Cations*
beav	*88 - 95*	0.019	0.032	0.012	0.008	0.072	0.0002	0.007	0.002	0.0004	0.009
coldl	*88 - 95*	0.021	0.045	0.024	0.010	0.099	-0.002	0.010	0.002	-0.0001	0.009
drayt	*93 - 95*	0.022	0.121	0.032	0.016	0.190	-0.007	0.036	0.009	0.009	0.046
eller	*88 - 91*	0.018	0.064	0.017	0.007	0.107	-0.001	-0.022	-0.001	0.0001	-0.025
esth	*87 - 98*	0.021	0.109	0.038	0.008	0.176	-0.001	0.005	0.002	0.0002	0.006
ftch	*89 - 95*	0.033	0.080	0.020	0.011	0.145	0.006	0.025	0.004	0.0004	0.035
ftmc	*88 - 95*	0.030	0.089	0.049	0.007	0.176	-0.003	0.003	-0.0006	0.0006	0.0007
ftver	*88 - 95*	0.029	0.120	0.027	0.016	0.192	0.003	0.016	0.002	0.002	0.023
highp	*88 - 95*	0.018	0.165	0.039	0.026	0.248	-0.0008	-0.018	-0.004	-0.003	-0.025
kana	*88 - 95*	0.012	0.074	0.028	0.005	0.119	-0.0008	0.012	0.002	0.0003	0.013
redd	*88 - 95*	0.013	0.084	0.028	0.006	0.131	-0.001	0.003	-0.001	-0.0002	0.001
royal	*92 - 95*	0.020	0.098	0.029	0.007	0.154	-0.008	0.029	0.005	-0.0004	0.026
suff	*88 - 95*	0.051	0.219	0.066	0.017	0.353	-0.005	0.0009	0.002	-0.001	-0.003
camp	*94 - 96*	0.193	0.023	0.033	0.015	0.226	-0.059	n/a	n/a	0.004	-0.027
castl	*93 - 96*	0.039	0.070	0.015	0.013	0.137	-0.009	-0.034	-0.0005	-0.003	-0.046
cranb	*89 - 90*	0.063	0.228	0.156	0.018	0.466	0.026	-0.054	-0.083	0.011	-0.100
erich	*89 - 92*	0.094	0.138	0.024	0.014	0.270	-0.0002	0.006	-0.0009	-0.002	0.003
kamwes	*89 - 94*	0.039	0.055	0.015	0.017	0.126	-0.004	-0.018	-0.003	-0.003	-0.027
kelow	*89 - 94*	0.057	0.050	0.013	0.019	0.139	-0.008	0.008	0.0002	-0.003	-0.002
nanoo	*89 - 95*	0.088	0.034	0.018	0.019	0.153	-0.001	0.003	0.001	-0.0002	-0.004
pend	*89 - 90*	0.151	0.017	0.036	0.012	0.216	0.114	0.009	0.034	0.003	0.160
porth	*89 - 94*	0.272	0.008	0.055	0.020	0.355	-0.003	-0.0001	0.001	0.0007	-0.001
satur	*89 - 94*	0.176	0.010	0.037	0.014	0.238	0.004	0.0005	0.0008	0.0005	0.005
smith	*89 - 90*	0.074	0.515	0.062	0.031	0.682	0.113	-0.775	-0.073	0.004	-0.732
squam	*89 - 96*	0.067	0.009	0.013	0.011	0.099	0.002	-0.002	-0.001	-0.0005	-0.002
vict	*89 - 96*	0.203	0.025	0.046	0.016	0.289	-0.001	-0.005	-0.0001	-0.002	-0.008
creel	*83 - 93*	0.014	0.027	0.015	0.007	0.063	-0.001	-0.001	0.0001	0.0003	-0.002
casc	*84 - 97*	0.034	0.008	0.012	0.004	0.058	-0.0004	-0.0007	-0.001	-0.0001	-0.002
giveo	*82 - 97*	0.087	0.191	0.074	0.018	0.370	0.005	-0.0002	0.0003	0.002	0.007
havre	*85 - 97*	0.029	0.034	0.019	0.007	0.089	-0.001	-0.004	-0.001	-0.00002	-0.007
sulli	*84 - 87*	0.037	0.041	0.021	0.007	0.106	-0.008	-0.023	-0.008	-0.002	-0.041

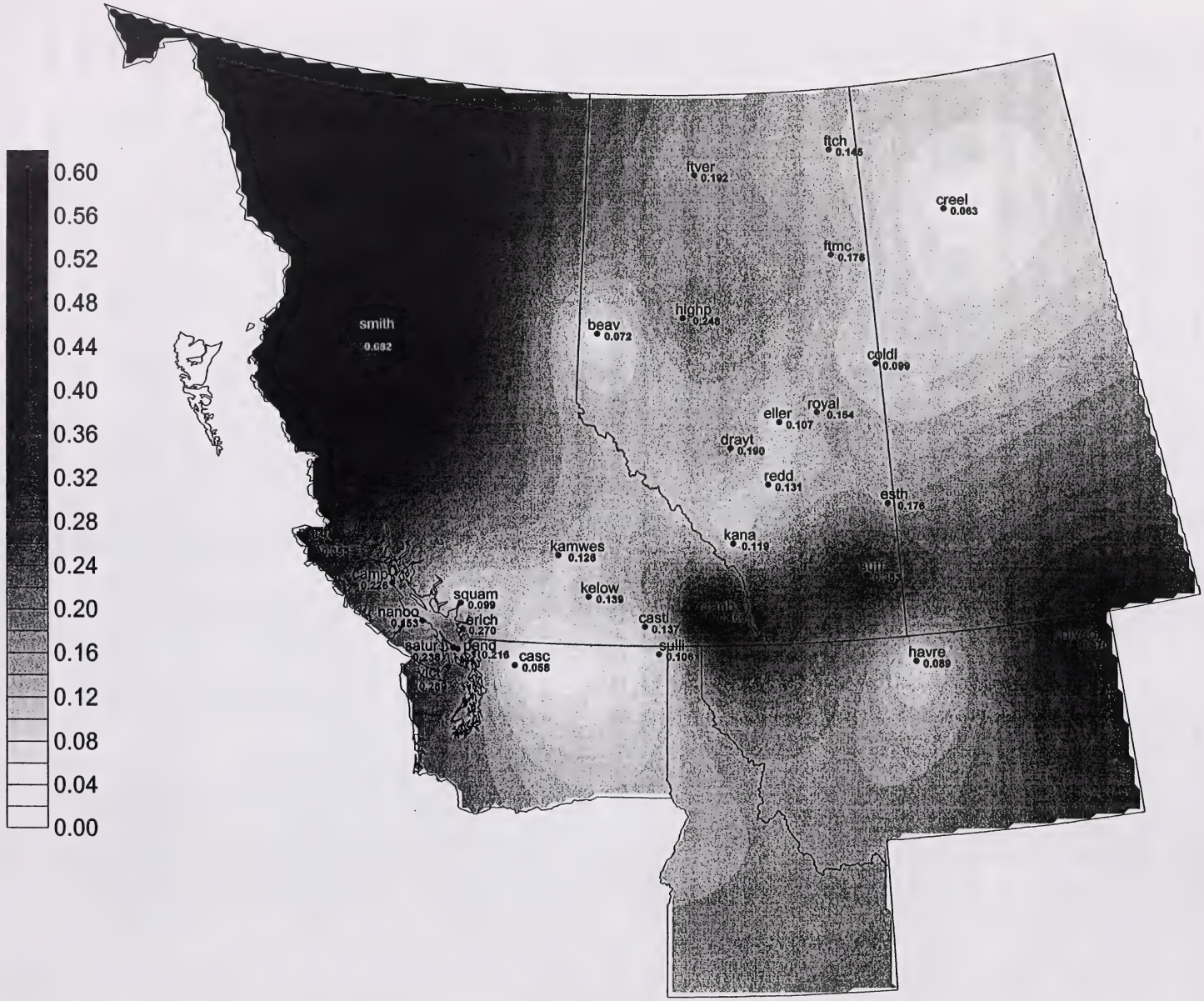


Figure 4.4 Mean annual dry deposition of base cations (keq/ha), based on Ontario regression

Table 4.4 Mean annual dry deposition and annual dry deposition trends, using Alberta regression

		Mean Annual Dry Deposition (keq/ha)					*Annual Dry Deposition Trends (keq/ha/yr)*				
Station	**Years**	*Na*	*Ca*	*Mg*	*K*	*Cations*	*Na*	*Ca*	*Mg*	*K*	*Cations*
beav	*88 - 95*	0.009	0.024	0.006	0.004	0.044	0.0001	0.0008	0.0004	0.0001	0.001
coldl	*88 - 95*	0.010	0.026	0.009	0.004	0.050	-0.0007	0.0009	0.0004	-0.00003	0.0005
drayt	*93 - 95*	0.010	0.033	0.011	0.006	0.060	-0.002	0.003	0.002	0.002	0.005
eller	*88 - 91*	0.009	0.028	0.008	0.004	0.048	-0.0004	-0.002	-0.0003	0.00004	-0.003
esth	*87 - 98*	0.008	0.032	0.012	0.004	0.056	-0.0002	0.0004	0.0004	0.00004	0.0007
ftch	*89 - 95*	0.014	0.028	0.008	0.005	0.055	0.002	0.003	0.0009	0.0001	0.006
ftmc	*88 - 95*	0.013	0.030	0.015	0.004	0.062	-0.0009	0.0003	-0.0001	0.0002	-0.0005
ftver	*88 - 95*	0.013	0.033	0.010	0.006	0.061	0.001	0.002	0.0005	0.0004	0.003
highp	*88 - 95*	0.007	0.037	0.012	0.009	0.065	-0.0003	-0.002	-0.0008	-0.0007	-0.003
kana	*88 - 95*	0.007	0.029	0.010	0.003	0.049	-0.0003	0.001	0.0003	0.0001	0.001
redd	*88 - 95*	0.008	0.030	0.010	0.003	0.050	-0.0004	0.0003	-0.0002	-0.00005	-0.0003
royal	*92 - 95*	0.008	0.031	0.010	0.004	0.053	-0.003	0.003	0.001	-0.0001	0.0009
suff	*88 - 95*	0.020	0.042	0.018	0.006	0.087	-0.002	0.0001	0.0005	-0.0003	-0.001
camp	*94 - 96*	0.068	0.022	0.011	0.006	0.085	-0.020	n/a	n/a	0.001	-0.003
castl	*93 - 96*	0.016	0.028	0.007	0.005	0.057	-0.003	-0.003	-0.0001	-0.0007	-0.007
cranb	*89 - 90*	0.024	0.043	0.038	0.007	0.112	0.009	-0.005	-0.018	0.003	-0.011
erich	*89 - 92*	0.035	0.034	0.009	0.005	0.084	-0.0001	0.0005	-0.0002	-0.0005	-0.0002
kamwes	*89 - 94*	0.014	0.027	0.007	0.006	0.055	-0.001	-0.002	-0.0006	-0.0009	-0.004
kelow	*89 - 94*	0.022	0.027	0.007	0.007	0.062	-0.003	0.0007	0.0001	-0.0007	-0.003
nanoo	*89 - 95*	0.033	0.024	0.008	0.007	0.067	-0.0004	0.0009	0.0003	-0.0001	-0.003
pend	*89 - 90*	0.054	0.023	0.012	0.005	0.093	0.039	0.002	0.007	0.0007	0.049
porth	*89 - 94*	0.095	0.022	0.016	0.007	0.140	-0.0009	0.0003	0.0003	0.0002	-0.0001
satur	*89 - 94*	0.063	0.022	0.012	0.006	0.102	0.001	0.0003	0.0002	0.0001	0.002
smith	*89 - 90*	0.028	0.068	0.017	0.010	0.123	0.038	-0.069	-0.016	0.001	-0.046
squam	*89 - 96*	0.026	0.020	0.006	0.005	0.056	0.0005	-0.002	-0.0005	-0.0001	-0.002
vict	*89 - 96*	0.072	0.022	0.013	0.006	0.113	-0.0005	-0.002	-0.0002	-0.0005	-0.003
creel	*83 - 93*	0.008	0.024	0.007	0.004	0.042	-0.0005	-0.0002	0.00001	0.0001	-0.0006
casc	*84 - 97*	0.014	0.020	0.006	0.003	0.043	-0.0001	-0.0001	-0.0003	-0.00002	-0.0005
giveo	*82 - 97*	0.032	0.039	0.020	0.007	0.097	0.002	-0.0002	0.0001	0.0004	0.002
havre	*85 - 97*	0.013	0.025	0.008	0.004	0.049	-0.0005	-0.0005	-0.0003	-0.00001	-0.001
sulli	*84 - 87*	0.016	0.026	0.008	0.004	0.053	-0.003	-0.002	-0.002	-0.0005	-0.007

Figure 4.5 is a plot of mean annual dry deposition at each station, based on the Alberta regression. Dry deposition calculated with the Alberta regression was lower in magnitude than wet deposition. The ratio of dry to wet deposition is shown in Figure AI.3 in the appendix.

When Figures 4.4 and 4.5 are compared, it is apparent that the Alberta regression estimated less dry deposition than the Ontario regression for western Canada. Both methods, however, estimated the greatest dry deposition of base cations in western BC.

Figure 4.5 Mean annual dry deposition of base cations (keq/ha), based on Alberta regression

5.0 TOTAL DEPOSITION

The total deposition of base cations (wet plus dry) was calculated for each of the stations in the study area, using the dry deposition estimates from both regressions (Ontario and Alberta). Mean annual total deposition was investigated, as well as annual trends in total base cation deposition over the available years of data at each station.

Table 5.1 gives mean annual total deposition, annual total deposition trends, and the total deposition over the available time period for each station. These results are based on dry deposition values from each of the Ontario and Alberta regressions.

5.1 Estimates Using Eder-Dennis Equations

Mean annual total deposition of all cations is plotted for each station in Figure 5.1, based on the Ontario regression. Mean annual total base cation deposition ranged from 0.09 to 1.36 keq/ha when the Ontario regression was applied to the stations. The greatest mean annual total deposition value (1.36 keq/ha) was found on the west coast, at Port Hardy.

Some other high total deposition values were estimated at High Prairie, Cranbrook Airport, Suffield, Give Out Morgan, and the other stations on and near the west coast. Mean annual total deposition minima were estimated at the Cree Lake, Beaverlodge, and Havre Experiment stations.

Annual trends in total deposition of base cations ranged from -0.8 keq/ha/y at Smithers PCC to 0.2 keq/ha/y at Pender Isl, based on the Ontario regression. In general, however, most total deposition trends were negative, suggesting that the deposition of base cations in western Canada has generally decreased.

5.2 Estimates Using Relationships from Beaverlodge and Esther Data

When the Alberta regression was applied to precipitation monitoring stations in western Canada, mean annual total deposition values ranged from 0.07 to 1.15 keq/ha. As shown in Figure 5.2, the greatest mean annual total deposition of base cations (1.15 keq/ha) was estimated at Port Hardy. This was the same station where the highest total deposition was found using the Ontario regression; however, the value was higher (1.36 keq/ha). Also analogous to the results of the Ontario regression, areas of low mean annual total deposition were estimated at and surrounding the Cree Lake, Beaverlodge, and Havre Experiment stations using the Alberta regression.

When considering annual trends in total deposition, the Alberta regression gave a general decrease in total base cation deposition at most stations, as did the Ontario regression. However, the Alberta regression generally gave smaller decreasing trends in total deposition than the trends resulting from the Ontario regression. The Alberta regression resulted in annual total deposition trends ranging from -0.08 keq/ha/y at East Richmond and Smithers PCC to 0.10 keq/ha/y at Campbell River. Similar to the Ontario regression, the Alberta regression showed that the deposition of base cations has generally decreased in western Canada since the 1980s.

Table 5.1 Total deposition in western Canada, based on Ontario and Alberta regressions

		Eder-Dennis (Ontario) Regression			Alberta Regression		
Station	Years	Mean Ann. (keq/ha)	Trend (keq/ha/yr)	Total Dep. (keq/ha)	Mean Ann. (keq/ha)	Trend (keq/ha/yr)	Total Dep. (keq/ha)
beav	88 - 95	0.11	0.01	0.91	0.09	0.003	0.69
coldl	88 - 95	0.18	0.002	1.43	0.13	-0.007	1.03
drayt	93 - 95	0.32	0.08	0.95	0.19	0.04	0.56
eller	88 - 91	0.18	-0.02	0.72	0.12	-0.002	0.48
esth	87 - 98	0.22	0.007	2.63	0.10	0.001	1.19
ftch	89 - 95	0.23	0.05	1.61	0.14	0.02	0.98
ftmc	88 - 95	0.24	0.004	1.90	0.12	0.003	0.99
ftver	88 - 95	0.23	0.02	1.87	0.10	0.002	0.82
highp	88 - 95	0.42	-0.06	3.36	0.24	-0.04	1.90
kana	88 - 95	0.23	0.02	1.86	0.16	0.01	1.29
redd	88 - 95	0.21	0.01	1.67	0.13	0.008	1.02
royal	92 - 95	0.26	0.04	1.03	0.16	0.02	0.62
suff	88 - 95	0.47	-0.01	3.78	0.21	-0.01	1.65
camp	94 - 96	0.48	0.07	1.44	0.34	0.10	1.01
castl	93 - 96	0.21	-0.05	0.86	0.13	-0.01	0.54
cranb	89 - 90	0.53	-0.1	1.06	0.18	-0.06	0.35
erich	89 - 92	0.64	-0.08	2.55	0.45	-0.08	1.81
kamwes	89 - 94	0.16	-0.03	0.98	0.09	-0.007	0.55
kelow	89 - 94	0.20	-0.009	1.17	0.12	-0.01	0.71
nanoo	89 - 95	0.29	-0.02	2.00	0.20	-0.02	1.40
pend	89 - 90	0.35	0.2	0.70	0.23	0.07	0.46
porth	89 - 94	1.36	-0.07	8.18	1.15	-0.07	6.89
satur	89 - 94	0.49	-0.03	2.96	0.36	-0.03	2.15
smith	89 - 90	0.77	-0.8	1.55	0.22	-0.08	0.43
squam	89 - 96	0.30	-0.04	2.39	0.25	-0.04	2.04
vict	89 - 96	0.51	-0.03	4.04	0.33	-0.02	2.63
creel	83 - 93	0.09	-0.004	1.02	0.07	-0.002	0.79
casc	84 - 97	0.22	0.0009	3.12	0.21	0.003	2.92
giveo	82 - 97	0.42	0.005	6.79	0.15	0.0002	2.43
havre	85 - 97	0.12	-0.007	1.58	0.08	-0.002	1.05
sulli	84 - 87	0.15	-0.04	0.61	0.10	-0.007	0.40

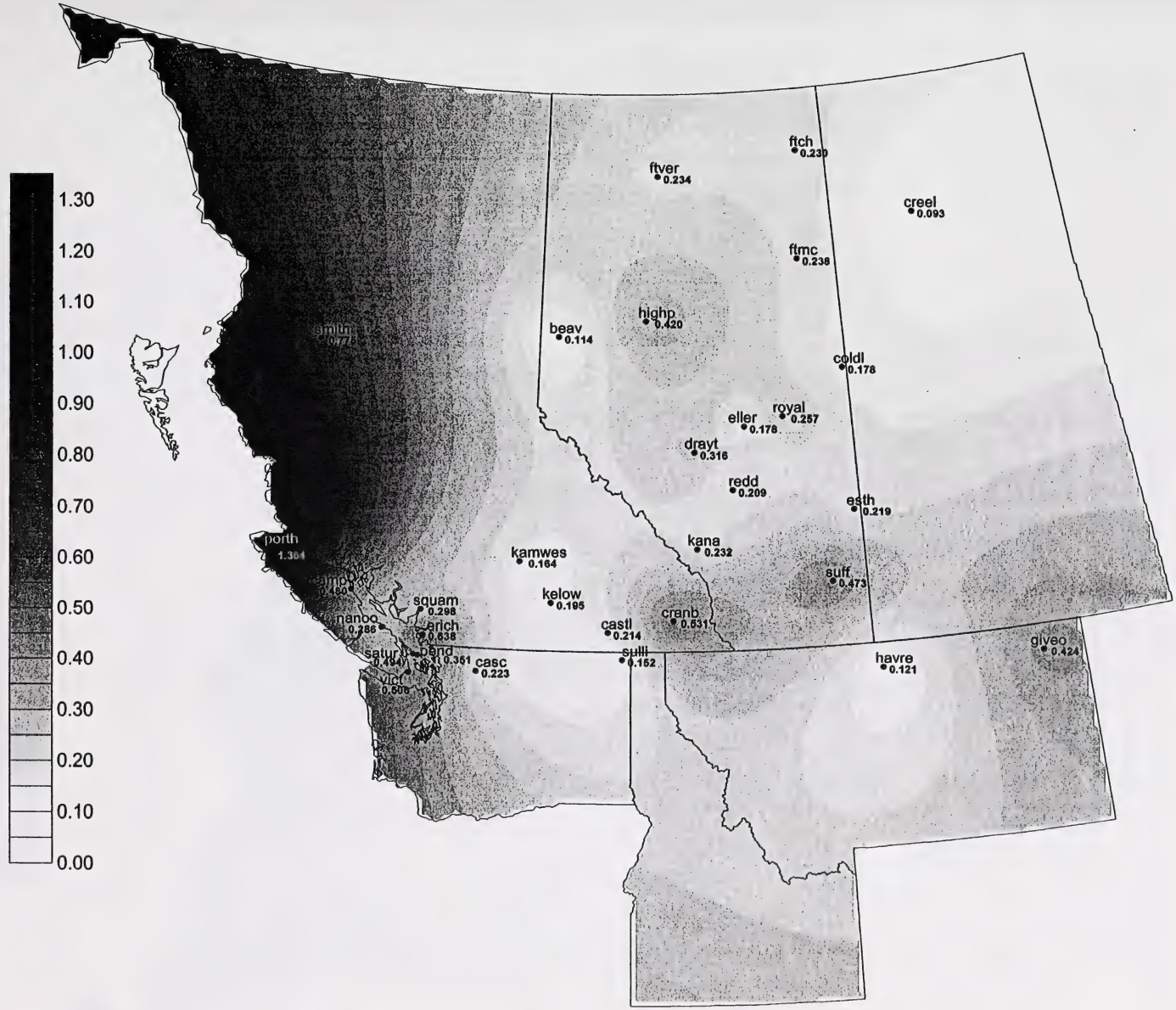


Figure 5.1 Mean annual total base cation deposition (keq/ha), based on Ontario regression

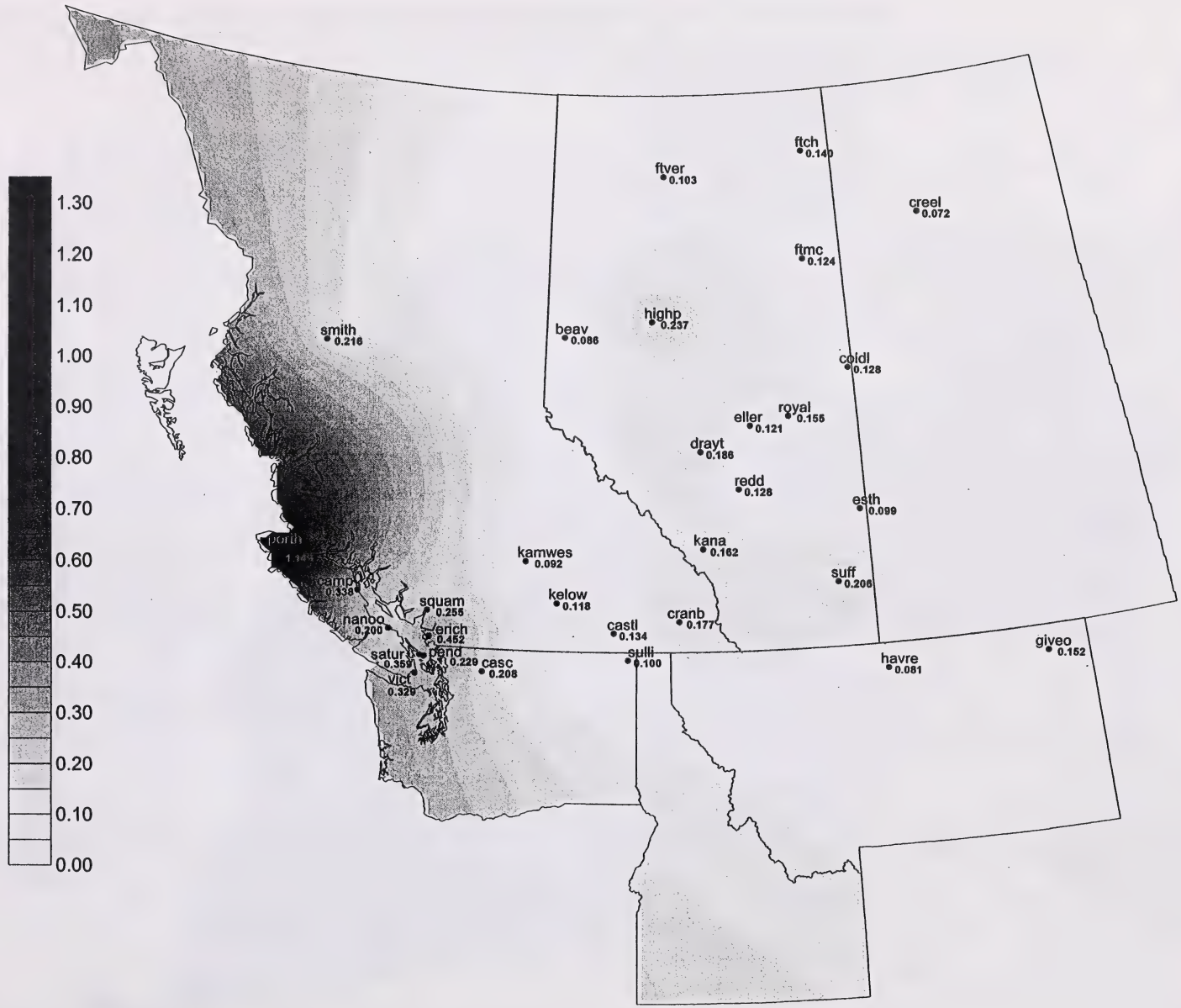


Figure 5.2 Mean annual total base cation deposition (keq/ha), based on Alberta regression

Overall, the base cation deposition estimates using the Alberta regression equations were lower than the estimates from the Ontario (Eder-Dennis) regression equations. However, even though the magnitude of deposition varied between the two estimation methods, the two regressions gave similar spatial variations and patterns of highs and lows across western Canada. This is not surprising, considering that the precipitation chemistry field controls the pattern of deposition, regardless of which set of regression equations is used for estimating air concentrations. In general, the greatest base cation deposition was estimated in the west coast area, mainly as a result of Na^+.

6.0 CONCLUSIONS

Both precipitation concentrations and wet deposition of base cations were quite variable from year to year at each station. The greatest wet deposition was found in western British Columbia, and Na^+ and Ca^{2+} were the cations with the highest wet deposition values. The highest mean annual wet deposition value was found for Na^+ (0.745 keq/ha), at Port Hardy on the west coast. The lowest wet deposition values, on average, were found for K^+.

Wet deposition was generally greatest in western BC and decreased to the east of the study area. Wet deposition of Ca^{2+}, however, had peaks in both central Alberta and southwestern BC. Mean annual wet deposition of total cations ranged from 0.030 to 1.009 keq/ha across western Canada, with the highest mean annual wet deposition value (1.009 keq/ha) at Port Hardy. In terms of wet deposition trends, 18 of the 31 stations had decreasing wet deposition over time. However, only 7 stations had wet deposition trends that were significant at the 5% level.

Two sets of linear regression equations were used to estimate base cation air concentrations, one derived from Ontario data by Eder and Dennis (1990) (the 'Ontario regression') and one derived from data at Beaverlodge and Esther (the 'Alberta regression'). Overall, it appears that the Ontario regression was not suitable for western Canada, because air concentrations estimated by the Ontario regression were higher than the directly measured concentrations at Beaverlodge and Esther. The Alberta regression provides an alternative method of calculating air concentrations of base cations; however, it cannot be tested for suitability over western Canada because evaluation data are not available. A study should be carried out to obtain measured air concentrations at more stations, so that a better relationship can be derived and tested for the western part of the country.

Dry deposition values were estimated from air concentrations calculated from both the Ontario and Alberta relationships. Mean annual dry deposition, based on the Ontario regression, ranged from 0.058 to 0.682 keq/ha, with the greatest dry deposition occurring at the Smithers PCC station in western BC. Dry deposition values given by the Ontario regression were greater than wet deposition values. Mean annual dry deposition values based on the Alberta regression were lower, ranging from 0.042 to 0.140 keq/ha, with the greatest dry deposition occurring at Port Hardy, in western BC. In addition, the dry deposition values from the Alberta regression were lower than wet deposition values.

The magnitude of base cation deposition was lower using the Alberta regression, but the two relationships gave similar spatial variations between stations in western Canada. Most base cation deposition occurs on the west coast, mainly as a result of Na^+. The greatest total deposition was found at Port Hardy for both the Ontario and Alberta regressions, with mean annual total deposition values of 1.364 keq/ha and 1.149 keq/ha, respectively. The result of both regressions was that deposition of base cations has generally decreased in western Canada since the 1980s. However, the trends from the Alberta regression were smaller in magnitude than the trends from the Ontario regression.

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8.0 APPENDIX

Table AI.1 Coefficient of variation for average precipitation concentrations in a year (%)

Station	Years	*Na*	*Ca*	*Mg*	*K*	*Cations*
beav	88 - 95	23	53	46	30	35
coldl	88 - 95	51	33	28	63	27
drayt	93 - 95	36	22	28	80	25
eller	88 - 91	33	40	19	53	31
esth	87 - 98	37	24	25	28	23
ftch	89 - 95	96	123	100	41	98
ftmc	88 - 95	63	72	113	54	72
ftver	88 - 95	59	81	93	135	81
highp	88 - 95	27	91	83	76	69
kana	88 - 95	32	43	35	34	37
redd	88 - 95	44	35	25	39	32
royal	92 - 95	68	34	37	29	27
suff	88 - 95	45	39	22	38	29
camp	94 - 96	40	n/a	n/a	31	29
castl	93 - 96	39	72	13	42	46
cranb	89 - 90	30	14	38	49	5
erich	89 - 92	15	33	16	26	18
kamwes	89 - 94	36	55	54	68	52
kelow	89 - 94	37	34	12	54	21
nanoo	89 - 95	30	62	40	65	44
pend	89 - 90	55	38	68	18	49
porth	89 - 94	19	27	15	25	18
satur	89 - 94	13	26	19	23	11
smith	89 - 90	111	98	85	9	55
squam	89 - 96	26	36	17	47	15
vict	89 - 96	21	21	42	37	22
creel	83 - 93	68	58	34	126	60
casc	84 - 97	16	52	57	48	21
giveo	82 - 97	150	117	117	186	131
havre	85 - 97	29	50	40	62	34
sulli	84 - 87	46	37	54	52	41

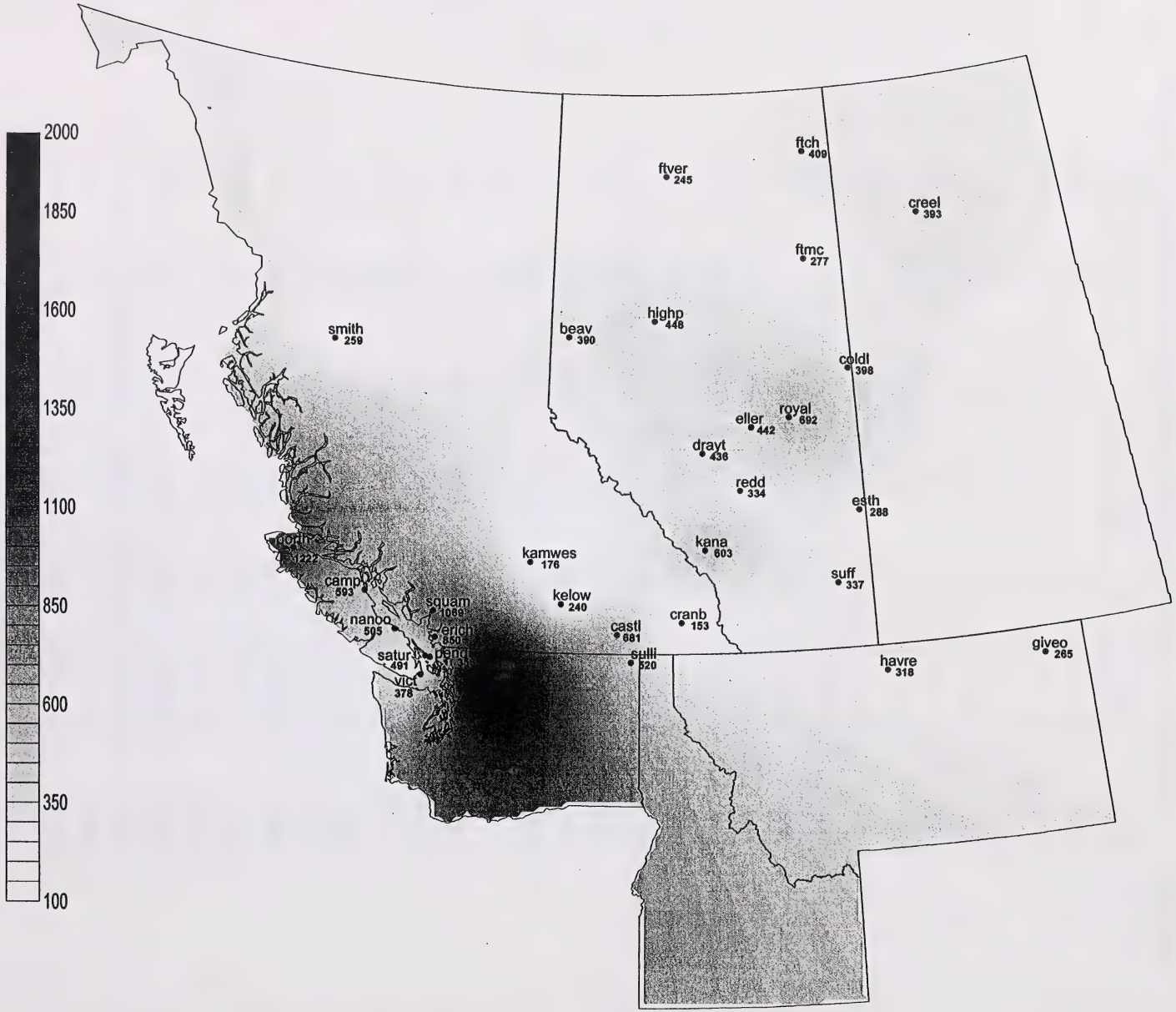

Figure AI.1 Mean annual precipitation (mm)

Table AI.2 Average annual wet deposition (keq/ha)

Station	Years	H+	SO4	XSO4	NO3	Cl	NH4
beav	88 - 95	0.036	0.051	0.051	0.026	0.008	0.019
coldl	88 - 95	0.020	0.071	0.071	0.046	0.008	0.071
drayt	93 - 95	0.041	0.108	0.109	0.050	0.008	0.085
eller	88 - 91	0.029	0.111	0.111	0.058	0.009	0.093
esth	87 - 98	0.021	0.046	0.046	0.036	0.003	0.050
ftch	89 - 95	0.033	0.058	0.058	0.016	0.021	0.019
ftmc	88 - 95	0.043	0.076	0.076	0.026	0.010	0.021
ftver	88 - 95	0.015	0.031	0.031	0.016	0.006	0.022
highp	88 - 95	0.021	0.059	0.059	0.033	0.011	0.037
kana	88 - 95	0.049	0.113	0.113	0.056	0.008	0.054
redd	88 - 95	0.017	0.087	0.087	0.047	0.005	0.081
royal	92 - 95	0.042	0.104	0.104	0.063	0.005	0.112
suff	88 - 95	0.010	0.078	0.078	0.068	0.013	0.090
camp	94 - 96	0.083	0.081	0.057	0.081	0.223	0.027
castl	93 - 96	0.184	0.265	0.265	0.069	0.022	0.084
cranb	89 - 90	0.005	0.025	0.025	0.017	0.006	0.015
erich	89 - 92	0.100	0.216	0.195	0.121	0.201	0.072
kamwes	89 - 94	0.013	0.025	0.025	0.029	0.009	0.025
kelow	89 - 94	0.009	0.028	0.028	0.038	0.018	0.052
nanoo	89 - 95	0.065	0.078	0.070	0.056	0.079	0.052
pend	89 - 90	0.042	0.055	0.045	0.025	0.103	0.007
porth	89 - 94	0.040	0.156	0.070	0.038	0.840	0.049
satur	89 - 94	0.074	0.095	0.074	0.055	0.201	0.023
smith	89 - 90	0.005	0.016	0.016	0.013	0.014	0.004
squam	89 - 96	0.174	0.159	0.145	0.123	0.142	0.028
vict	89 - 96	0.061	0.102	0.084	0.043	0.170	0.025
creel	83 - 93	0.041	0.049	0.049	0.022	0.005	0.019
casc	84 - 97	0.147	0.118	0.105	0.085	0.121	0.039
giveo	82 - 97	0.012	0.047	0.047	0.033	0.007	0.038
havre	85 - 97	0.013	0.034	0.034	0.031	0.006	0.033
sulli	84 - 87	0.021	0.037	0.036	0.029	0.009	0.015

Table AI.3 Annual wet deposition trends (keq/ha/y)

Station	Years	H+	SO4	XSO4	NO3	Cl	NH4
beav	88 - 95	0.001	0.001	0.001	-0.0005	-0.001	0.004
coldl	88 - 95	-0.001	-0.011	-0.011	-0.006	-0.001	-0.008
drayt	93 - 95	0.004	0.006	0.006	0.007	0.001	0.001
eller	88 - 91	-0.004	-0.008	-0.008	-0.002	0.0005	-0.003
esth	87 - 98	0.0004	0.001	0.001	0.001	0	0.001
ftch	89 - 95	-0.005	-0.002	-0.002	-0.002	-0.0003	0.0002
ftmc	88 - 95	0.005	0.007	0.007	0.002	-0.001	0.004
ftver	88 - 95	-0.001	-0.004	-0.004	-0.002	-0.0003	-0.004
highp	88 - 95	-0.001	-0.009	-0.009	-0.005	-0.003	-0.008
kana	88 - 95	0.002	0.001	0.001	-0.0001	-0.001	0.003
redd	88 - 95	-0.0001	0.001	0.001	0.001	-0.0004	0.006
royal	92 - 95	0.007	0.003	0.003	0.007	0.0002	0.007
suff	88 - 95	0.001	-0.010	-0.010	-0.009	-0.003	-0.011
camp	94 - 96	0.029	0.023	0.019	0.026	0.059	0.006
castl	93 - 96	0.050	0.041	0.041	0.012	0.002	0.022
cranb	89 - 90	-0.005	-0.010	-0.010	-0.009	-0.003	-0.003
erich	89 - 92	-0.016	-0.043	-0.038	-0.024	-0.050	-0.011
kamwes	89 - 94	0.0003	0.0002	0.0002	0.001	-0.001	0.003
kelow	89 - 94	0.0000	-0.004	-0.004	-0.006	-0.004	-0.005
nanoo	89 - 95	-0.017	-0.012	-0.011	-0.011	-0.014	0.008
pend	89 - 90	-0.025	-0.030	-0.032	-0.008	0.019	-0.005
porth	89 - 94	-0.002	-0.015	-0.008	-0.002	-0.056	-0.008
satur	89 - 94	-0.009	-0.008	-0.005	-0.007	-0.029	-0.004
smith	89 - 90	-0.001	-0.002	-0.002	0.001	-0.001	0.0005
squam	89 - 96	-0.019	-0.024	-0.023	-0.014	-0.019	-0.001
vict	89 - 96	-0.010	-0.018	-0.017	-0.008	-0.008	-0.004
creel	83 - 93	-0.001	-0.004	-0.004	-0.001	-0.001	-0.0001
casc	84 - 97	0.004	-0.001	-0.002	0.003	0.002	0.002
giveo	82 - 97	0.001	0.001	0.001	0.001	0.0001	0.002
havre	85 - 97	0.001	0.0004	0.0004	0.001	0	0.002
sulli	84 - 87	-0.0001	-0.0002	-0.0003	0.002	-0.0001	0.002

Table AI.4 Standard deviation of annual wet deposition (keq/ha)

Station	Years	*Na*	*Ca*	*Mg*	*K*	*Cations*
beav	88 - 95	0.003	0.01	0.002	0.001	0.01
coldl	88 - 95	0.01	0.02	0.009	0.005	0.04
drayt	93 - 95	0.002	0.02	0.008	0.009	0.04
eller	88 - 91	0.003	0.009	0.003	0.002	0.02
esth	87 - 98	0.002	0.01	0.003	0.001	0.02
ftch	89 - 95	0.01	0.03	0.008	0.007	0.05
ftmc	88 - 95	0.009	0.03	0.02	0.003	0.05
ftver	88 - 95	0.002	0.004	0.002	0.002	0.007
highp	88 - 95	0.006	0.2	0.04	0.02	0.2
kana	88 - 95	0.004	0.03	0.008	0.001	0.03
redd	88 - 95	0.001	0.03	0.006	0.002	0.04
royal	92 - 95	0.008	0.03	0.008	0.002	0.05
suff	88 - 95	0.01	0.03	0.01	0.005	0.06
camp	94 - 96	0.05	n/a	n/a	0.01	0.1
castl	93 - 96	0.01	0.02	0.005	0.002	0.03
cranb	89 - 90	0.003	0.02	0.01	0.0001	0.03
erich	89 - 92	0.13	0.07	0.03	0.01	0.2
kamwes	89 - 94	0.003	0.01	0.002	0.002	0.02
kelow	89 - 94	0.009	0.005	0.002	0.006	0.02
nanoo	89 - 95	0.03	0.02	0.008	0.01	0.07
pend	89 - 90	0.01	0.003	0.006	0.003	0.01
porth	89 - 94	0.38	0.02	0.07	0.02	0.5
satur	89 - 94	0.13	0.01	0.03	0.008	0.2
smith	89 - 90	0.001	0.02	0.002	0.001	0.02
squam	89 - 96	0.06	0.03	0.02	0.01	0.1
vict	89 - 96	0.05	0.01	0.009	0.007	0.08
creel	83 - 93	0.003	0.01	0.003	0.002	0.02
casc	84 - 97	0.04	0.01	0.01	0.002	0.05
giveo	82 - 97	0.004	0.02	0.01	0.002	0.04
havre	85 - 97	0.003	0.01	0.004	0.001	0.01
sulli	84 - 87	0.004	0.002	0.001	0.001	0.005

Table AI.5 Coefficient of variation for annual wet deposition of base cations (%)

Station	Years	*Na*	*Ca*	*Mg*	*K*	*Cations*
beav	88 - 95	36	42	37	29	31
coldl	88 - 95	89	48	55	69	50
drayt	93 - 95	21	29	37	66	30
eller	88 - 91	41	19	23	54	24
esth	87 - 98	50	41	36	36	40
ftch	89 - 95	78	68	71	72	64
ftmc	88 - 95	109	74	105	86	85
ftver	88 - 95	32	17	33	55	17
highp	88 - 95	74	149	154	92	134
kana	88 - 95	48	37	31	22	30
redd	88 - 95	29	53	43	71	46
royal	92 - 95	81	49	45	47	49
suff	88 - 95	63	47	52	67	47
camp	94 - 96	22	n/a	n/a	54	42
castl	93 - 96	36	71	94	14	35
cranb	89 - 90	34	55	56	2	49
erich	89 - 92	76	51	76	45	61
kamwes	89 - 94	32	60	55	40	43
kelow	89 - 94	51	21	39	62	37
nanoo	89 - 95	48	52	47	64	53
pend	89 - 90	12	13	32	29	8
porth	89 - 94	51	36	49	43	49
satur	89 - 94	74	45	72	51	69
smith	89 - 90	7	34	21	6	24
squam	89 - 96	53	76	73	57	55
vict	89 - 96	35	42	29	54	36
creel	83 - 93	79	81	57	76	72
casc	84 - 97	34	48	36	35	29
giveo	82 - 97	41	82	77	60	65
havre	85 - 97	47	61	57	57	45
sulli	84 - 87	37	8	20	24	12

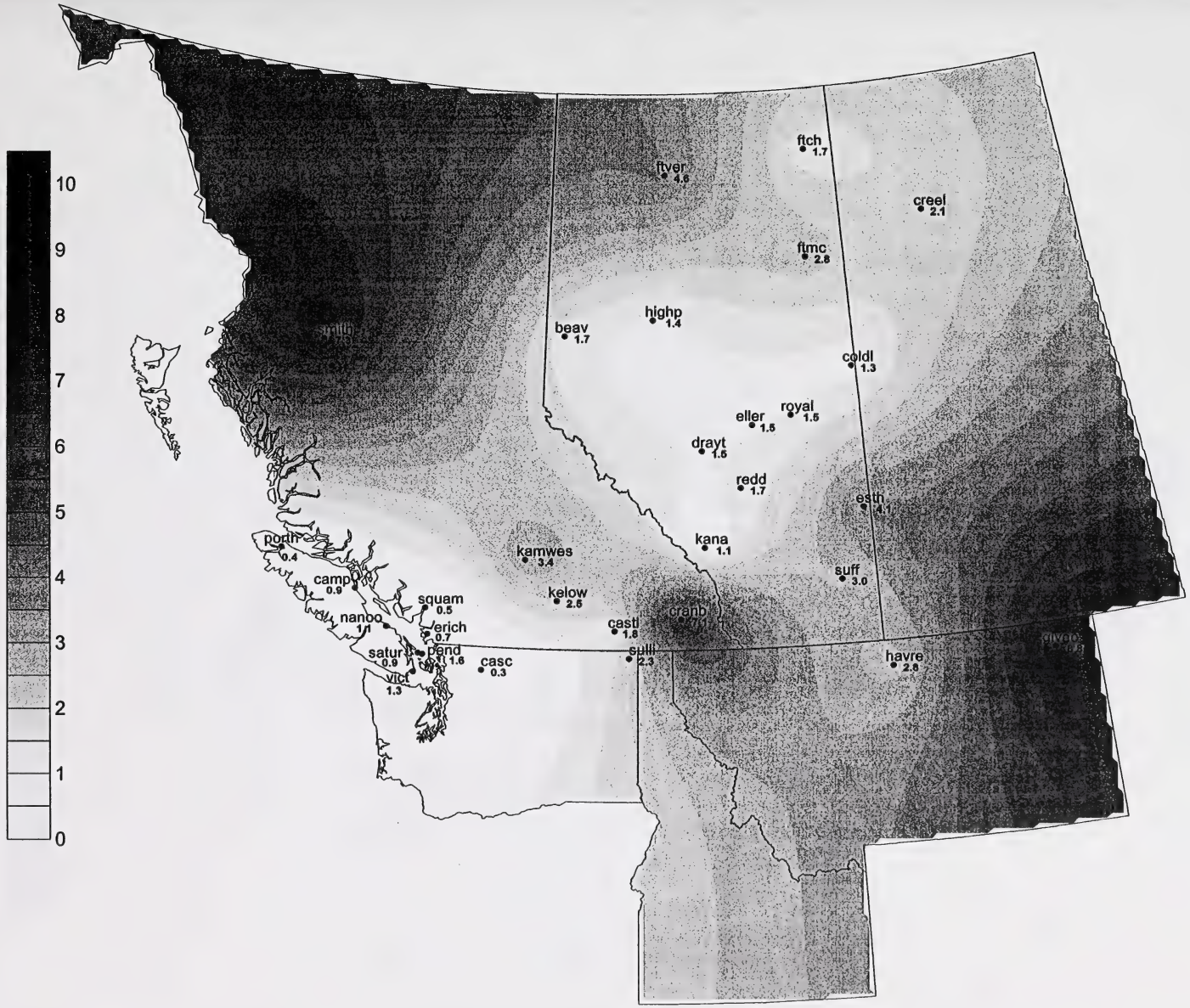

Figure AI.2 Ratio of mean annual dry deposition to mean annual wet deposition for all cations, based on Ontario regression

Figure AI.3 Ratio of mean annual dry deposition to mean annual wet deposition for all cations, based on Alberta regression

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